ASSESSMENT OF FUEL CELLS AND PRESSURIZED WATER NUCLEAR REACTORS FOR SUBMARINE PROPULSION

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by

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B.S. in O.E. U.S. Naval Academy
(1972)

Submitted in partial fulfillment of the requirements for the Degree of Ocean Engineer and the Degree of Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

December 1976

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Submitted to the Department of Ocean Engineering and Mechanical Engineering on 17 December 1976, in partial fulfillment of the requirements for the degree of Ocean Engineer and the degree of Master of Science in Mechanical Engineering at the Massachusetts Institute of Technology.

ABSTRACT

Nuclear reactors have been powering U.S. Navy submarines for over twenty years with basically the same power plant, the pressurized water reactor. The hydrogen-oxygen fuel cell, with technology learned from the Space Program, offers a possible alternate for selected missions. Employing a math model based on existing nuclear powered submarines, but modified to encompass the fuel cell submarine, the effects of the two power plant types on payload carrying capabilities, maximum velocities, endurances, and capital cost are studied.

The fuel cell submarine is feasible at low vehicle sizes (1000 tonnes) at low shaft horsepower (5000 HP). The nuclear submarine is not. When comparing payload carrying capabilities, the two power plant types offer similar capabilities for endurance values of 2000 and 4000 miles for the fuel cell submarines. However, in the capital cost area, the fuel cell submarine cost is 65% to 85% of the nuclear submarine cost with savings of 18 to 60 million dollars. While the fuel cell submarine cannot compete with nuclear submarines in endurance, there are some missions where fuel cell submarines can do the job, at lower costs.

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ACKNOWLEDGEMENTS

I thank my thesis advisor, Professor Phillip Mandel, for all his guidance and help which he provided me throughout my course of study. I also thank Mike Drooker for his valuable assistance. Finally, I thank my wife, Linda, for her patience and understanding in bearing with me during my time at M.I.T.

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DEFINITION OF SYMBOLS USED

Symbol	Definition	Units
C	Capital Cost	$\$ \times 10^{-3}$
ΔC_f	Additional Roughness Coefficient	--
C_p	Prismatic Coefficient	--
D	Submarine Diameter	feet
D[I]	Vehicle Mass	TONNES
E[I]	Endurance	Nautical miles
G	Vertical Center of Gravity Fraction of Hull Diameter	--
H	Total Labor Hours	Man hours
H1↔H9	Group Labor Man Hours	Man hours
k	Proportional Constant	$HP/[(LTONS)^{2/3}(KTS)^3]$
K	Proportional Constant	$HP/[(LTONS)^{2/3}(KTS)^3]$
K1	Fuel Cell Power	KW
L(I)	Non-Propulsive Electric Load	KW
M	Total Material Cost	$
M1-M9	Group Material Cost	$
N1	# Enlisted	Men
N2	# CPO's	Men
N3	# Officers	Men
N4	Total Personnel	Men
P1	Payload Mass	TONNES
P2	Payload Volume	m^3

P9	Correction Factor	--
R1	Payload Mass/Vehicle Mass	--
R2	Payload Volume/Vehicle Volume	--
R3	Payload Density	kg/m^3
RPM	Shaft Revolutions/minutes	rev/min
SHP, S1	Shaft Horsepower	HP
S[I]	Shaft Horsepower/1000	HP
T	Total Vertical Moment	FT TONNES/FT
T1-T9	Group Vertical Moment	FT TONNES/FT
t_D	Test Depth	feet
V	Total Volume	m^3
V1-V9, V_p, V_{pr}	Group, Personnel, Provision Volume	m^3
W	Total Mass	TONNES
W1-W9, W_p, W_{pr}	Group, Personnel, Provision Mass	TONNES
X	Vehicle Volume	m^3
Y	Velocity	KNOTS
Z1-Z7, Z_p, Z_{pr}	Vertical Center of Gravity	feet
ζ_2-ζ_7, ζ_{pr}	Group Provision Density	kg/m^3
ζ_s	Density of Steel	lb/ft^3
σy	Yield Strength	psi

CHAPTER I

INTRODUCTION

Prior to the launching of the nuclear powered submarine, USS NAUTILUS, in 1954, all combat submarines were powered by a combination of diesel generators and batteries. When unable to snorkel, the submarine could only remain submerged for a limited amount of time. With the advent of nuclear power, submarines were freed from the surface, and became true submarines, limited in submergence time by personnel requirements rather than by power requirements. With the exception of the diesel-electric powered BARBEL class, all combat submarines built for the U.S. Navy since 1954 have been powered by nuclear reactors. There are over 100 nuclear powered submarines in the U.S. Navy today, with power plants essentially the same as the NAUTILUS.

One of the benefits of the space program was the advancement in fuel cell technology. Fuel cells were used in both the GEMINI and APOLLO space missions and fuel cells will provide electric power in the Space Shuttle. Fuel cells consume oxygen and hydrogen and produce direct current electricity and water. Based on the performance of fuel cells in the space program, and the advantages in weight and volume, fuel cells offer an interesting alternative to nuclear power for submarines of modest size and endurance. One of the DSRV's, a U.S. Navy submarine rescue submersible, is being equipped with a fuel cell to extend its endurance over that possible with batteries of the current technology.

I.A. Methodology

Independent inputs in this study are vehicle mass, configuration, and type and size of power plant. Outputs include maximum speed, payload mass and volume, limiting center of gravity location, endurance range at cruising speed, and capital costs. (See Figure 1.)

I.A.1. Vehicle Mass

Vehicle mass was limited to four inputs: 1000, 2000, 5000, and 10000 tonnes. This range includes all existing submarines in the U.S. Navy.

I.A.2. Configuration

The vehicle was constrained to a body of revolution, single screw submarine with a prismatic coefficient of 0.70 and a length to diameter ratio of 9.0. The maximum horsepower per shaft was limited to 100,000 H.P. Therefore based on these two constraints, the input power was limited to 100,000 H.P. As the results will show, however, submarines with greater than 100,000 H.P. were infeasible for other reasons. The maximum operating depth was fixed at 400 m. (1312 ft.) and the crush depth at 600 meters (1969 ft.). The operating depth was fixed in order to calculate a respresentative hull mass. Payload masses would increase with decreasing depth. HY-80 steel was used for the hull material. The propeller was constrained to being a fully submerged, fixed pitch propeller with a diameter two-thirds the hull

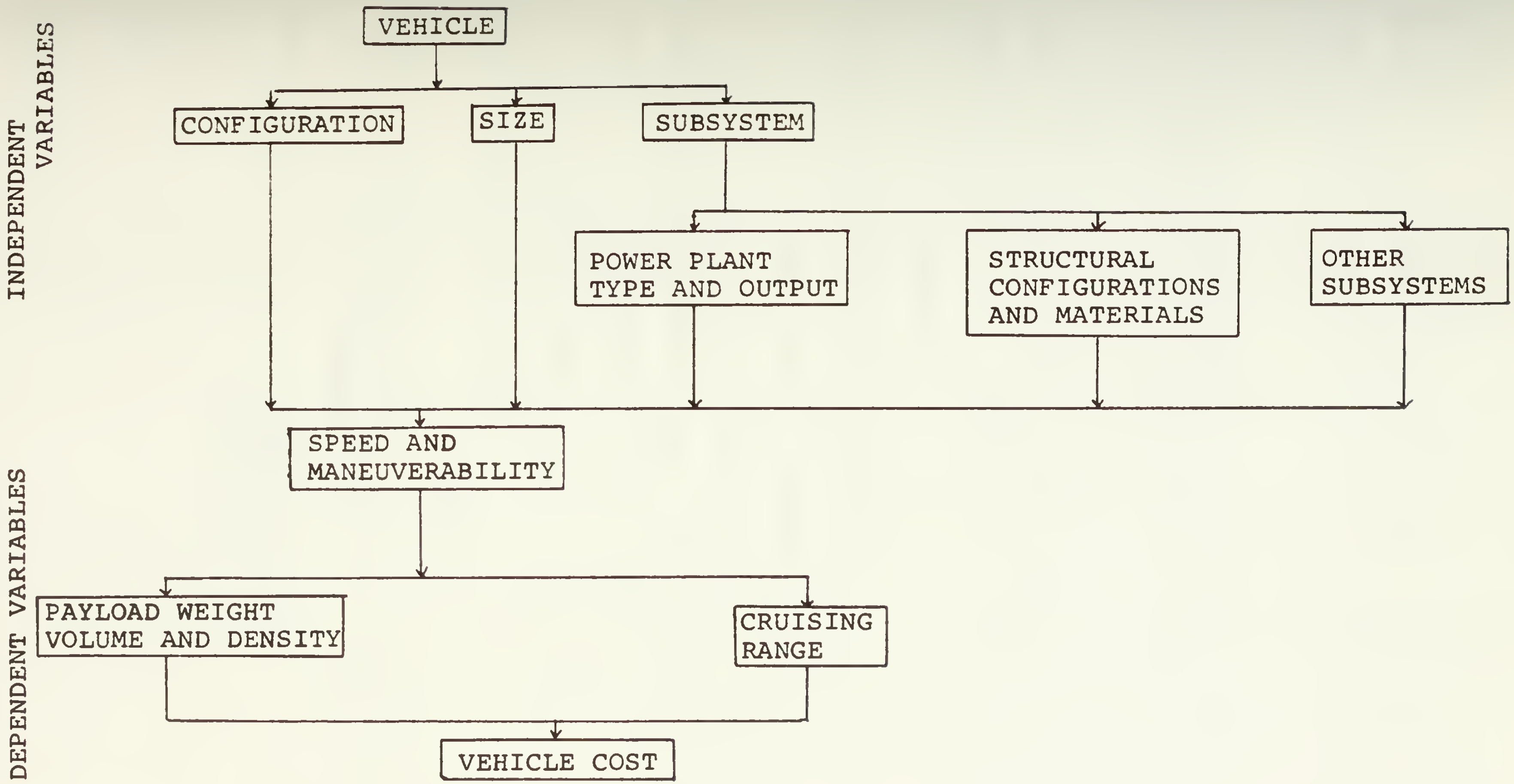


FIGURE 1 - METHODOLOGY

diameter. The vehicle density was fixed by bouyancy requirements at the density of sea water, 1025 kg/m^3 (64 lb/ft^3). This configuration is typical of nuclear powered attack submarines.

I.A.3 Types and Power Outputs of Power Plants

There were two types of power plants studied; the pressurized water nuclear reactor and the hydrogen-oxygen fuel cell. The power output inputted into this study range from 5000 to 400,000 H.P. However, all power plants above 100,000 H.P. proved infeasible.

I.A.3.a. Nuclear Power Reactors

Nuclear reactors generate heat by the fission of uranium. There are four basic types of nuclear reactors generating electricity today: the pressurized water reactor (PWR), the boiling water reactor (BWR), gas cooled reactor, and liquid metal cooled reactor. See Table 1 for a comparison of reactor core types.

TABLE 1

Comparison of Representative Power Densities for a 500 MW (Thermal) Reactors (Ref. 1)

Reactor Type	Representative Power Density (MW(Thermal)/ft^3)	Area Volume (ft^3)
PWR	2.5	200
BWR	0.8	650
Gas Cooled	0.25	2000
Liquid Metal	25.0	20

While the liquid metal reactor core is the smallest due to high coolant heat transfer coefficients, other problems concerning radioactivity requiring heavy shielding, chemical activity, corrosion and thermal shock make this power plant a difficult choice for marine propulsion. The USS SEAWOLF, a U.S. Navy submarine built in 1957, was powered by a liquid metal cooled reactor, but it was replaced after two years by a PWR.

The BWR is less suitable for marine use due to design constraints on the control rods, necessitating that the reactor vessel be mounted relatively high in the ship. Another potential difficulty in marine use of a BWR plant is reactivity changes associated with void movement and volume change due to ship motions caused by shock, impact, and seaway forces. (Ref. 1)

The PWR is the best choice for marine nuclear propulsion today. It consists of a primary and a secondary system. The primary system deals with equipment which contacts the main coolant of the reactor. It consists of the reactor core, steam generators, a pressurizer to absorb transients, coolant pumps to remove heat from the core and transport it to the steam generator, and the necessary piping and shielding. The steam generator transfers the heat from the coolant to the steam of the secondary system.

The secondary system is a basic Rankine cycle steam power plant, with the boiler replaced by a steam generator. The output of the steam generator is saturated steam at 700-1000 psia and 500-550°F. (See Figure 2)

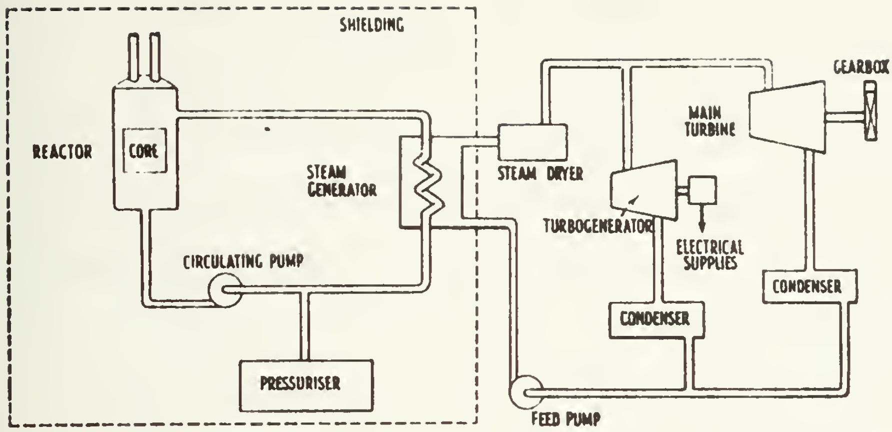


FIGURE 2. BASIC CIRCUIT OF A PRESSURIZED WATER REACTOR (Ref 12)

I.A.3.b. Fuel Cells

Fuel cells convert chemical energy directly into electrical energy, primarily using hydrogen and oxygen as the reactants in a reverse electrolysis process. (See Figure 3)

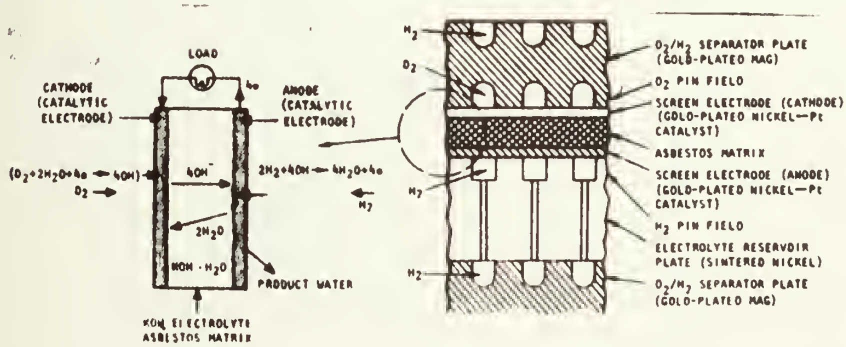


FIGURE 3. H_2-O_2 FUEL CELL -- CELL DESIGN (Ref 2)

When compared with fuel cells using ammonia, methanol, or hydrocarbons, either directly in the fuel cell or by using reformers to produce hydrogen to use in a hydrogen-oxygen fuel cell, the hydrogen-oxygen fuel cell using hydrogen and oxygen at the reactants offers the best choice. As shown in Table 2, the H_2-O_2 fuel cell has the lowest specific weight and volume, lowest noise output, lowest heat rejection rate, highest thermal efficiency, best consistent response and starting characteristics, and the simplest design.

The hydrogen-oxygen fuel cell has been used in both the APOLLO and GEMINI space programs with great success, and will be used to supply electrical power in the space shuttle. The data on the H_2-O_2 fuel cell used in this study was taken from information on the fuel cell designed for use in the space shuttle. It offered the most extensive and up to date data available in the literature. (See Table 3 for some details.)

	APOLLO PROGRAM	TECHNOLOGY PROGRAM	SHUTTLE PROGRAM
LIFE (HOURS	400	5000	2000 5000 (WITH MAINTENANCE)
SUSTAINED POWER (KW)	0 9	5	7
PEAK POWER (KW)	1.4	10	12
SPECIFIC WEIGHT (LB/KW)	170	30-40	35
SPECIFIC VOLUME (FT^3/KW)	5 8	0.25	0.96
START-STOP CYCLES	12	UNLIMITED	125

TABLE 3. A COMPARISON OF FUEL CELL REQUIREMENTS FOR APOLLO, NASA TECHNOLOGY, AND THE SHUTTLE PROGRAM (Ref 2)

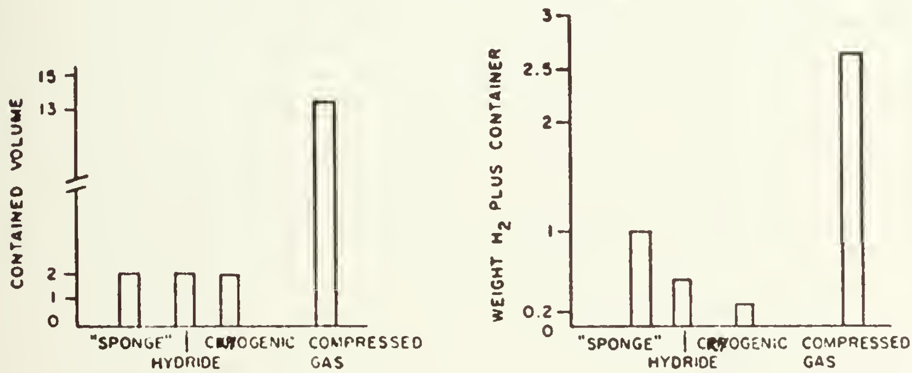
I.A.3.c. Fuel Storage Systems

Hydrogen and oxygen are gases at atmospheric temperatures and pressures, with very low densities. There are three feasible ways of storing hydrogen: as a high pressure

TABLE 2. COMPARISON OF FUEL CELL TYPES (Ref 7)

	DIRECT				INDIRECT - H_2-O_2 fuel cell		
Fuel	H_2	Ammonia (40°C)	Hydrocarbon (200°C)	Methanol	Ammonia	Hydro-carbon	Methanol
Electrolyte	Akaline	Akaline	Acid	Acid			
Weight/power (lbs/KW)	26	31	125	165	68	65	52
Volume/power (ft^3/KW)	0.41	0.47	1.64	1.88	1.32	1.21	1.00
Heat rejection ratio (KW/KW)	0.85	1.27	1.33	1.38	1.06	0.93	1.28
Total reactants (lb/KWH)	0.925	1.930	1.800	2.100	1.886	1.563	2.040
Energy costs (¢/KWH)	9.25	9.25	7.68	10.10	8.99	6.72	9.80
Projected plant life hours	2500-4000	400-800	400-800	500-1000	2500-4000	2500-4000	2500-4000
Noise	low	intermediate	inter-mediate	inter-mediate	high	high	high
Transient Response Start-Up	1(best)	2	3	2	4	5	6
Simplicity	1(best)	2	3	2	4	5	6

gas, a cryogenic liquid or in a metal hydride. Alternative ways of producing hydrogen from hydrocarbons were ruled out based on complexities, further heat rejection requirements, and lack of reliability. Table 2 shows the disadvantages of this method. Figure 4 shows comparitive volumes and weights for hydrogen storage systems. After deciding the submarine could not absorb the penalty of the extra weight of the metal hydride system, the storage system chosen for hydrogen was cryogenics. Cryogenic storage for oxygen was also chosen. The safety problem is probably the greatest with cryogenic storage but with proper design and handling, this system will be no more dangerous than a nuclear reactor.



STORAGE SYSTEM	"SPONGE"	HYDRIDE	CRYOGENIC	COMPRESSED GAS
STORAGE TEMPERATURE	AMBIENT	AMBIENT	-423° F	AMBIENT
STORAGE PRESSURE	30-45 PSI	AMBIENT	AMBIENT	2000 PSI
OPERATING TEMP	AMBIENT	530°F	-423° F	AMBIENT

"SPONGE" SYSTEM • H_2 ABSORBED IN $LaNi_5$ RARE EARTH COMPLEX

HYDRIDE SYSTEM • MAGNESIUM HYDRIDE

FIGURE 4. COMPARISON OF VARIOUS HYDROGEN STORAGE SYSTEMS (Ref 17)

I.B. Assessment

The outputs of the math model are maximum velocity, payload mass and volume, cruising range, and capital cost. A submarine is considered infeasible when its payload mass or volume is less than zero. The two power plant types will be assessed by two methods: Maximum velocity feasible based on vehicle size, power, endurance, and payload mass fraction, and capital cost based on vehicle size, and power, or based on size and maximum velocity.

CHAPTER II

MATH MODEL

The math model described in this section is based on Ref. 5, Conceptual Design of Submarines (CODESUB). The study is based on data from existing U.S. Navy submarines, both attack type and ballistic missile carrying and is constrained to nuclear propulsion plants, and hulls which are body of revolutions and single-shaft configurations. The displacement ranges are from 2607 to 8251 LTONS. CODESUB takes the NAVSHIPS weight groups and breaks it into finer groups. (See Table 4) This study will use the NAVSHIPS weight groups.

NAVSHIPS Weight Groups	Code Sub Weight Groups
1. Hull	1. Hull
2. Propulsion	2. Main Propulsion
3. Electric	3. Electric
4. Communication and Control	4. Communication and Control
5. Auxiliary Systems	5. Auxiliary Systems
6. Outfit and Furnishings	6. Outfit and Furnishings
7. Armament	7. Armament
Loads	8. Battery
	9. Emergency Propulsion Motor
	10. Personnel
	11. Variable Load
	12. Emergency Fuel
	13. Water Ballast
	14. Fixed Ballast
	15. Special Payload
	16. Cargo

TABLE 4. NAVSHIPS AND CODESUB WEIGHT GROUPS

The CODESUB program strives to remove payload items from the NAVSHIPS weight groups. Payload items are divided into three types; electronic equipment normally in NAVSHIPS Group 4, Communication and Control, weapons systems including all expendable items such as torpedoes and mines, (normally NAVSHIPS Group 7) and cargo, including cargo handling gear. This program is ideally suited to the task set out in this study; calculating weights solely based on displacement and power. Part of the payload in this study will be the personnel other than that required to run the submarine and its propulsion plant.

Unfortunately, CODESUB is based on only a limited number of submarines, and does not include the latest nuclear submarines, the SSN688 LOS ANGELES class or the TRIDENT submarines. Comparisons with data from these classes plus data from a design study on a 60,000 SHP submarine does lend support to the CODESUB program. Maximum errors less than 10%.

The controlling factor in the CODESUB program is weight. Based on weight, volumes, labor hours and material, costs are calculated. Weight is the most easily obtained data on submarines and therefore is the most accurate.

Cost analysis from CODESUB is in 1971 dollars. Man hours and material costs are converted to 1976 dollars in this study. CODESUB breaks down cost into two groups, labor and material. In addition, the basic CODESUB construction cost differs from the NAVSHIPS basic construction cost by including the cost of

government furnished equipment. The resulting equations in CODESUB sometimes results in large differences from empirical values but the estimated values are considered more realistic for predicting costs for conceptual submarines since market conditions, status of learning, etc., are difficult to forecast.

In order to calculate cost information in 1976 dollars, several changes were made. Due to inflation the cost of material was incremented by 75.4%. Changes in productivity resulted in an increase of 15% in the man-hours. Labor man-hour rate was $6.84/man-hour and design and engineering labor rate was $8.79/man-hour. Profit and overhead accounted for another 5% and 8% respectively of the total capital cost.

The center of gravity calculations were followed exactly from CODESUB. The center of gravity for the required payload was calculated to insure the feasibility of the design.

II.A. Size and Power Calculations

Displacement is fixed as an independent input. Using the data listed in CODESUB, a value for the prismatic coefficient, C_p and L/D (length/diameter) ratio was chosen. Based on attack submarines, a value of 0.70 for C_p and a value of 9.0 for L/D were chosen. These values are necessary inputs into powering calculations. (See Table 5 for sizing information) Powering calculations are detailed in Appendix I. The results are based on the equation:

$$\text{Power} = k\Delta^{2/3}\,V^3$$

Appendix I details the selection of k, which is a function of speed, L/D, diameter (calculated from C_p), and an additional roughness allowance, ΔC_f which was assumed to be 0.0004.

TABLE 5

Characteristics of Input Submarines

Δ (tonnes)	C_p	L/D	L (ft)	D (ft)	Propeller Diameter (ft)
1000	0.70	9.0	172	19.1	12.7
2000	0.70	9.0	216.5	24.1	16.0
5000	0.70	9.0	294	32.7	21.8
10000	0.70	9.0	370.5	41.1	27.4

II.B. Hull - Group 1

The hull group includes the pressure hull and pressure proof enclosures whose mass is dependent on test depth and yield strength of the hull material, the associated framing and bulkheads, and foundations for equipment included in the other groups. Inputs into the equation are displacement, test depth, (t_D) which is two-thirds of crush depth, yield strength of the steel (σ_y), density of the steel (ζ_s), and main propulsion mass (W2).

$$W1 = [0.1597 + (3.473 + 0.018\ \zeta_s)(t_D/\sigma_y)]\ \Delta + 0.1451[W2]$$

(see Table 6)

$\zeta_s = 495\ \text{lb/ft}^3$ $\qquad t_D = 1312\ \text{ft}$ $\qquad \sigma_y = 80{,}000\ \text{psi}$

TABLE 6

Group 1 Masses in Tonnes

NUCLEAR

SHP	Δ-1000	2000	5000	10000
5000	421	784	1872	3686
10000	452	815	1903	3717
20000	504	866	1955	3769
30000	549	912	2000	3814
40000	591	954	2042	3856
50000	631	994	2082	3896
60000	669	1032	2121	3935
80000	743	1106	2194	4008
100000	814	1177	2265	4079

FUEL CELL

SHP	Δ-1000	2000	5000	10000
5000	390	756	1852	3678
10000	414	780	1876	3702
20000	461	827	1924	3750
30000	508	874	1971	3798
40000	556	922	2019	3845
50000	603	969	2066	3893
60000	650	1017	2114	3941
80000	745	1111	2209	4037
100000	840	1206	2304	4132

NOTE: Fuel cell masses do not include fuel tank mass which would account for an additional 5-160 tons depending on the displacement and endurance.

The required volume for group 1 is taken as zero. This convention may be followed without discrepancy in the total required volume of the submarine because volumes required by other components are taken to the outside of the hull rather than to interior molded lines.

The center of gravity for hull mass is based on the hull diameter:

$$Z_1 = 0.4953D$$

Initial expection was that the center of gravity would be exactly half of the diameter, but the foundations and other equipment accounts for the difference.

It would be desirable to estimate costs for both labor hours and material for the pressure resistant portion of Group 1 separately from the other structures. This is because this portion requires more careful fabrication technique and the use of higher strength and more costly steels. However, the data breakdown does not permit this. All data used was based on an HY-80 hull material, so correction for different costs due to hull material was not necessary.

The labor hours for construction of the hull may be estimated by:

$$H1 = 13800\ (0.9842 \cdot W1)^{0.57}$$

The estimation equation for hull material dollars is:

$$M1 = 220302.4\ (0.9842 \cdot W1)^{0.41}$$

II.C. Main Propulsion - Group 2

The calculation process for main propulsion for each propulsion plant differs. The nuclear reactor calculations follow CODESUB. The fuel cell calculations are calculated differently.

II.C.1. Nuclear Reactor

This group includes the reactor, reactor vessel, energy converters, a large storage battery, emergency propulsion motor, and a number of other items. CODESUB assumes that the mass of some components varies directly with installed shaft horsepower, and the mass of other components varies directly with the square root of installed shaft horsepower. An additional correction is included to account for sound isolation of machinery. The mass of the storage battery and emergency propulsion motor is taken to be fixed. The equation is of the following form:

$$W2 = 4.462\ (SHP)^{1/2} + 0.0170\ (SHP) + 79.96 \quad \text{(see Table 7)}$$

The volume is calculated from the mass result, and a value for specific volume. Again a fixed value for the battery and EPM

is added. (see Table 7)

$$V2 = [(W2 - 79.96)(48.28) + 5865]\ 0.02832$$

The center of gravity is estimated from the following:

$$Z2 = 0.4505D$$

The cost of group 2 and group 3 (the electric plant) is calculated together due to their close relationship during construction. As in group 1, data scatter was considerable, and the estimation equations are guess estimates. The labor calculation is:

$$H2 + H3 = 679.1(W2 + W3)$$

The material equation, including the cost of government furnished equipment, is:

$$M2 + M3 = 4488.4(W2 + W3) + 43313\ W2$$

II.C.2. Fuel Cell

Fuel cell group 2 mass is calculated in four steps; estimating elective load, calculating the fuel cell mass, calculating the D.C. main propulsion motor mass, and calculating shafting, propeller, etc., mass. Based on installed

TABLE 7

Group 2 Masses and Volumes - Nuclear Reactor

	Group 2		Group 3	
SHP	Mass (tonnes)	Volume (m^3)	Mass (tonnes)	Volume (m^3)
5000	480	714	72	114
10000	696	1009	104	166
20000	1051	1494	158	250
30000	1363	1920	204	324
40000	1652	2316	248	393
50000	1928	2692	289	459
60000	2193	3055	329	522
80000	2702	3751	405	643
100000	3191	4420	479	760

shaft horsepower, and vehicle mass, the propulsive kilowatt load is calculated, assuming an efficiency of 90% for the D.C. motor, 10% parasitic loads within the fuel cell. An electric load for support equipment based on vehicle mass is then added (see Table 8). Based on this kilowatt load, a mass is calculated using a specific weight of 35 lb/KW. Propulsion motor mass is calculated using a 36 lb/HP specific weight and allowing a 10% error margin. Assuming a propeller diameter two-thirds the diameter of the ship, a shaft length a maximum of 20% the length of the ship, an equation based on shaft horsepower was used to calculate the remaining mass. Details are in Appendix II.

Volume calculations are also divided into three parts. The actual fuel cell volume is calculated using 0.96 ft^3/KW and then corrected by adding a 10% factor for errors. Main propulsion motor volume is calculated by using a specific volume of 0.1 ft^3/HP and correcting this figure by adding a 10% error margin also. Volume for the remaining group 2 is calculated using this specific volume from CODESUB and the mass of the remaining group. Masses and volumes are given in Table 9.

The center of gravity is taken to be identical to the nuclear reactor center of gravity:

$$Z2 = 0.4505D$$

TABLE 8

Fuel Cell Non Propulsive Elective Load and Fuel Consumption

Δ (tonnes)	Maximum Electrical Load (KW)	Fuel Consumption (50% load) (Kg/Hr)
1000	993	180.1
2000	1717	311.5
5000	3542	642.5
10000	6124	1110.9

TABLE 9

Fuel Cell Group 2 Masses (tonnes) and Volumes (m^3)

SHP	A-1000	2000	5000	10000
5000	188 tonnes / 181 m^3	209/213	264/298	344/422
10000	351/321	372/354	428/440	509/565
20000	678/603	699/636	756/723	839/851
30000	1004/884	1026/918	1083/1007	1168/1138
40000	1330/1166	1352/1200	1411/1290	1498/1424
50000	1656/1447	1679/1483	1738/1574	1828/1710
60000	1982/1729	2006/1765	2066/1857	2157/1996
80000	2635/2291	2659/2329	2721/2424	2817/2568
100000	3287/2854	3313/2894	3377/2991	3476/3141

The amount of labor required for construction of group 2 for fuel cells was assumed to be identical to nuclear power.

$$H2 = 679.1\ W2$$

The material costs for the fuel cell was also divided into three calculations. Due to the low level of mass produced fuel cells, the majority being prototypes designed for unique uses, an accurate cost figure on fuel cells is not available. Ref. 6 estimates the capital cost at $120/KW for a land-based, commercial power plant. Due to unique quality controls required by the Navy, plus other requirements based on shock, transients motions, and other military specifications, the cost to the Navy is probably higher. Not including the research and development cost, the cost used in this study was $500/KW. Costs for direct current propulsion motors were calculated using $100/HP. The remaining material cost of constructing group 2 was used using the cost data from CODESUB and the remaining group 2 weight. Labor hours were calculated using the total group 2 mass and the CODESUB labor figures from Group 2.

Details of fuel cell group 2 shafting and propeller mass calculations are given in Appendix II.

II.D. Electric Plant - Group 3

II.D.1. Nuclear Reactor

Electric plant mass includes the electric power generation equipment and the power distribution equipment. CODESUB uses vehicle mass to calculate this mass. While this may be correct for the limited number of power outputs used in CODESUB, for this study it is not adequate. Coolant pumps circulating water through the reactor core and steam generators constitute a major electric load. This load is a function of horsepower. Using both CODESUB and other data available in classified sources, electric plant weight was calculated using group 2 mass as an input.

$$W3 = 0.15\ W2$$

This equation allows for an electric load of 25% of the installed shaft horsepower.

CODESUB is used to calculate the volume:

$V3 = W3\ (1.587)$ (see Table 7 for Group 3 results)

The vertical center of gravity is a function of diameter:

$$Z3 = 0.5371\ D$$

The labor hours and material costs were calculated along with group 2 as the two groups are closely related during construction.

II.D.2. Fuel Cell

As the fuel cell generates direct current electricity, there is little need for energy converters. A majority of pumps which comprise a major electric load may be D.C. driven. A small capability for providing A.C. is necessary for controls and other normally A.C. available equipment. The electric plant mass is assumed to be both a function of shaft horsepower and displacement and is calculated in the following equation.

$$W3 = \frac{(SHP)}{10,000} + \frac{(\Delta)^{1/2}}{10}$$

The remainder of the fuel cells group 3 calculations are identical to the nuclear reactor case, using the calculated group 3 mass as an input. (see Table 10)

II.E. Communication and Control - Group 4

Group 4 calculations for both power plants are assumed to be identical. The majority of the mass in this group on a normal submarine is accounted for by the payload group. In this study this mass represents a small percentage of both the actual submarine mass and the total NAVSHIPS group 4 mass. Although CODESUB does make numerical estimates and derives

TABLE 10

Fuel Cell Group 3 Masses (TONNES) and Volumes (m^3)

SHP	Δ-1000	2000	5000	10000
5000	4 TONNES/6 m^3	5/8	8/12	11/17
10000	4/7	5/9	8/13	11/17
20000	5/8	6/10	9/14	12/19
30000	6/10	7/12	10/16	13/21
40000	7/11	8/13	11/18	14/22
50000	8/13	9/15	12/19	15/24
60000	9/15	10/17	13/21	16/25
80000	11/18	12/20	15/24	18/29
100000	13/21	14/23	17/27	20/32

a percentage of displacement for an answer, the reader is reminded that these are estimates and are subject to the judgement of the estimator. The displacement dependent part of group 4 mass is calculated from:

$$W4 = 0.0066\Delta$$

The volume of group 4 is calculated using the specific volume given in CODESUB:

$$V4 = W4 \cdot 1.5168$$

The center of gravity is a function of diameter,

$$Z4 = 0.75D$$

The labor hours and material costs for the displacement dependent part of group 4 are given as follows:

$$H4 = ((W4 \cdot (0.9842)^{0.76}) \ 5980 \quad \text{labor hours}$$

$$M4 = W4 \cdot (10012.5) \quad \text{material cost}$$

II.F. Auxiliary Systems - Group 5

Fuel cell group 5 mass was assumed to be less than the nuclear power mass for several reasons: 1) lower heat output at lower temperatures requiring a smaller airconditioning

and sea water cooling load, 2) smaller refrigeration and air conditioning loads due to smaller requirements for personnel, and 3) smaller life support requirements due to smaller requirements for personnel plus the elimination of either oxygen storage or generation for metabolic reasons by simply adding to fuel storage requirements. For the above reasons, the fuel cell group 5 mass was assumed to be 85% of the nuclear power group 5 mass, and calculations using this mass are also correspondingly less.

The following equations are used to estimate the necessary characteristics of group 5.

NUCLEAR	FUEL CELL	
W5 = DISPL (0.0771)	W5 = DISPL (0.0665)	mass
V5 = W5·(1.238)	same	volume
Z5 = D(0.5379)	same	center of gravity
$H5 = ((W5 \cdot 0.9842)^{0.52})30130$	same	labor hours
$M5 = ((W5 \cdot 0.9842)^{0.59})161368$	same	material cost

II.G. Outfit and Furnishings - Group 6 and Personnel

Group 6 calculations are functions of displacement, number of personnel, and endurance. This group is the combination of CODESUB's group 6 and 10. Endurance for group 6 calculations was fixed at 60 days. The difference between calculations for endurance power and fuel cells exists in the number of personnel required to man the necessary watch

stations at sea, and perform required maintenance. Nuclear reactors require a large number of personnel to run, while fuel cells require only a minimum number. Estimation of fuel cell manning is only a rough estimate. The fuel cell can be easy to run, based on existing smaller power plants. Table 11 gives manning levels for each power plant.

TABLE 11

Manning Levels for Submarine Power Plants

	Nuclear Power				Fuel Cell			
SHP	Officer N3	CPO N2	Enlisted N1	Total N4	Officer N3	CPO N2	Enlisted N1	Total N4
5000	3	3	23	29	2	2	11	15
10000	3	3	26	32	2	2	12	16
20000	4	4	33	41	3	3	14	20
30000	4	4	40	48	3	3	16	22
40000	4	5	46	55	3	4	18	25
50000	4	5	53	62	3	4	20	27
60000	4	6	60	70	3	5	22	30
80000	4	7	73	84	4	6	26	36
100000	5	8	86	99	4	7	30	41

Based on the above inputs, the following equations are used to estimate group 6 characteristics:

$$W_p + W_{pr} + W6 = [400(N3) + 330(N2) + 230(N1) + 420.6(N4)]/2205 + \Delta(0.02884)$$

$$V_p + V_{pr} + V6 = (N4)(7.557)$$

$$Z_p + Z_{pr} + Z6 = D \cdot 0.5422$$

$$H6 = 63.02\Delta$$

$$M6 = 230475.6\ (0.02838\Delta)^{0.37}$$

II.H. Armament - Group 7

Armament is classified as payload so all characteristics are zero.

II.I. Ballast

CODESUB classified variable loads as group 11 and water ballast as group 13 and fixed ballast (lead) as group 14. Lead is used both for a future growth margin and for stability. The minimum amount of lead used was assumed to be 4% of the displacement. Water ballast is limited to a minimum of 12% of the displacement in order to insure adequate reserve bouyancy on the surface. Variable loads, non-ballast water, consumable lube oil, compressed air, account for about 1.63% of the displacement. Incorporating these three groups into one, the following equations are used to obtain estimates of ballast characteristics:

$$W7 = 0.1763\ \Delta$$

$$V7 = 0.7759\ W7$$

$$Z7 = 0.3716\ D$$

$$M7 = 29.53\ \Delta$$

II.J. Fuel, Storage Tanks, and Endurance

Nuclear power reactors consume uranium fuel but this amount is negible. The amount of fuel required by nuclear power is assumed to be zero, and the endurance is only limited by personnel considerations, which limited mission time to sixty days. Endurance range is based on the speed maintained for sixty days.

Calculations for fuel cell requirements were much more difficult. Based on half of the non-propulsive load (Table 8), and endurance speed (10 kts was chosen), an electrical load on the fuel cell was estimated. Based on this load and the specific reactant consumption for the fuel cell (0.8 lb/KWH), the masses of the reactants were obtained. Using the ratio of 7.94 to 1 for the mass of oxygen to mass of hydrogen, and their respective densities ($O_2(\ell)$ - 71.4 lb/ft^3, ($H_2(\ell)$ 4.43 lb/ft^3), the volume of reactants was estimated.

The storage tank and insulation masses were estimated to be 20% of the reactant mass. Its volume was estimated using a specific volume of 0.3687 m^3/TONNES (density of 169.3 lb/ft^3).

II.K. Summary of Math Model

Table 12 summarizes the equations given in Sections II.B to II.J. The input value of vehicle mass minus the sum of masses included in Table 12 equals vehicle mass available for payload and fuel. Similarly the input value of total vehicle volume minus the sum of the volumes included in Table 12 equals vehicle volume available for payload and fuel. For any given vehicle, then, if endurance is fixed, the vehicle mass and volume available for payload are obtainable. If payload mass is fixed, both endurance and volume available for payload are obtainable. Data is given in Chapter III exploring both of these possibilities.

TABLE 12

Summary of Group Characteristics

	Nuclear Sub	Fuel Cell Sub
HULL		
	$W1 = 0.3628\Delta + 0.1451\ W2$	same
	$V1 = 0$	same
	$Z1 = 0.4953\ D$	same
	$H1 = 13800\ (0.9842\ W1)^{0.57}$	same
	$M1 = 220302.4\ (0.9842\ W1)^{0.41}$	same
MAIN PROPULSION		
	$W2 = 4.462\ (SHP)^{1/2} + 0.0170\ SHP + 80$	see Table 9
	$\zeta_2 = 731\ kg/m^3$ *	
	$Z2 = 0.4505\ D$	same
	$H2 = 679.1\ W2$	same
	$M2 = 47801.4\ W2$	(see Section II.C.2)
ELECTRICAL PLANT		
	$W3 = 0.15\ W2$	$W3 = SHP/10000 + \sqrt{\Delta}/10$
	$\zeta_3 = 630\ kg/m^3$	same
	$Z3 = 0.5371\ D$	same
	$H3 = 679.1\ W3$	same
	$M3 = 4488.4\ W3$	same
COMM & CONTROL		
	$W4 = 0.0066\ \Delta$	same
	$\zeta_4 = 659\ kg/m^3$	same
	$Z4 = 0.75\ D$	same
	$H4 = 5980(0.9842\ W4)^{0.76}$	same
	$M4 = 10012.5\ W4$	same

*This density applies only to first two terms of W2 equation.

TABLE 12 (cont)

AUX	
$W5 = 0.0771\ \Delta$	$W5 = 0.0665\ \Delta$
$\zeta_5 = 808\ kg/m^3$	
$Z5 = 0.5379\ D$	
$H5 = 30130\ (0.9842\ W5)^{0.52}$	same
$M5 = 161368\ (0.9842\ M5)^{0.59}$	
OUTFIT	
$W6 = 0.02884\ \Delta$	
$V6 = 0$	
$Z6 = 0.5422\ D$	same
$H6 = 63.02\Delta$	
$M6 = 230475.6\ (0.9842\ W6)^{0.37}$	
PERSONNEL	
$W_p = (400\ N3+330\ N2+230\ N1)/2205$	
$V_p = 7.137\ m^3/man$	
$Z_p = 0.5422\ D$	same
$H_p = 0$	
$M_p = 0$	
PROVISIONS	
$W_{pr} = 0.191\ N4$	
$\zeta_{pr} = 278\ kg/m^3$	
$Z_{pr} = 0.5422\ D$	same
$H_{pr} = 0$	
$M_{pr} = 0$	
BALLAST	
$W7 = 0.1763\ \Delta$	
$\zeta_7 = 1289\ kg/m^3$	
$Z7 = 0.3716\ D$	same
$M7 = 29.53\ \Delta$	

CHAPTER III

RESULTS

III.A. Nuclear Power

The mass fractions and volume fractions for each group for discrete shaft horsepower and vehicle masses are given in Table 13. Characteristics for a test depth of 400 meters (1212 ft) and 200 meters (606 ft) were included to allow the reader to judge the effect on payload the operating depth had. Obviously any total mass or volume fraction greater than one represents an infeasible submarine.

Figure 5 is a plot of payload mass and volume versus shaft horsepower. Figure 5 shows that a 2000 tonnes nuclear submarine is infeasible with more than 6500 H.P. (24 kts), a 5000 tonnes submarine with more than 29,500 H.P. (34 kts) and a 10000 tonnes submarine with more than 79,000 H.P. (41 kts). At these limits the submarines are mass limited. The volume limit on feasible vehicles would extend to higher power outputs. Figure 6 plots the density of the payload versus shaft horsepower. By knowing the density of the desired payload a design can be determined to be either mass or volume limited by using Figure 6. If the desired payload item has a lower density than shown in Figure 6, the design will be volume limited. Inputting shaft horsepower and vehicle size does constrain the payload density.

No nuclear submarine was infeasible based on vertical center of gravity requirements.

TEST DEPTH = 400 METERS

DISPL	VOL	SHP	MASS FRACTION GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL	VOLUME FRACTION GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL
1000	976	5000	0.421	0.480	0.072	0.007	0.077	0.029	0.009	0.176	1.271	0.000	0.732	0.117	0.010	0.098	0.000	0.225	0.140	1.322
2000	1951	5000	0.382	0.240	0.036	0.007	0.077	0.029	0.004	0.176	0.951	0.000	0.366	0.059	0.010	0.098	0.000	0.112	0.140	0.785
2000	1951	10000	0.408	0.348	0.052	0.007	0.077	0.029	0.005	0.176	1.102	0.000	0.517	0.085	0.010	0.098	0.000	0.124	0.140	0.974
5000	4878	5000	0.374	0.088	0.014	0.007	0.077	0.029	0.002	0.176	0.776	0.000	0.146	0.023	0.010	0.098	0.000	0.045	0.140	0.463
5000	4878	10000	0.381	0.139	0.021	0.007	0.077	0.029	0.002	0.176	0.832	0.000	0.207	0.034	0.010	0.098	0.000	0.059	0.140	0.539
5000	4878	20000	0.391	0.210	0.032	0.007	0.077	0.029	0.003	0.176	0.924	0.000	0.306	0.051	0.010	0.098	0.000	0.064	0.140	0.669
5000	4878	30000	0.400	0.273	0.041	0.007	0.077	0.029	0.003	0.176	1.006	0.000	0.394	0.067	0.010	0.098	0.000	0.074	0.140	0.783
10000	9756	5000	0.369	0.048	0.007	0.007	0.077	0.029	0.001	0.176	0.714	0.000	0.073	0.012	0.010	0.098	0.000	0.022	0.140	0.356
10000	9756	10000	0.372	0.070	0.010	0.007	0.077	0.029	0.001	0.176	0.742	0.000	0.103	0.017	0.010	0.098	0.000	0.025	0.140	0.393
10000	9756	20000	0.377	0.105	0.016	0.007	0.077	0.029	0.001	0.176	0.788	0.000	0.153	0.026	0.010	0.098	0.000	0.032	0.140	0.459
10000	9756	30000	0.381	0.136	0.020	0.007	0.077	0.029	0.001	0.176	0.828	0.000	0.197	0.033	0.010	0.098	0.000	0.037	0.140	0.516
10000	9756	40000	0.385	0.165	0.025	0.007	0.077	0.029	0.002	0.176	0.866	0.000	0.237	0.040	0.010	0.098	0.000	0.043	0.140	0.569
10000	9756	50000	0.388	0.193	0.029	0.007	0.077	0.029	0.002	0.176	0.902	0.000	0.276	0.047	0.010	0.098	0.000	0.048	0.140	0.619
10000	9756	60000	0.393	0.219	0.033	0.007	0.077	0.029	0.002	0.176	0.937	0.000	0.313	0.054	0.010	0.098	0.000	0.054	0.140	0.669
10000	9756	80000	0.401	0.270	0.041	0.007	0.077	0.029	0.003	0.176	1.003	0.000	0.384	0.066	0.010	0.098	0.000	0.065	0.140	0.764

TEST DEPTH = 200 METERS

DISPL	VOL	SHP	MASS FRACTION GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL	VOLUME FRACTION GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL
1000	976	5000	0.319	0.480	0.072	0.007	0.077	0.029	0.009	0.176	1.170	0.000	0.732	0.117	0.010	0.098	0.000	0.225	0.140	1.322
2000	1951	5000	0.290	0.240	0.036	0.007	0.077	0.029	0.004	0.176	0.860	0.000	0.366	0.059	0.010	0.098	0.000	0.112	0.140	0.785
2000	1951	10000	0.306	0.348	0.052	0.007	0.077	0.029	0.005	0.176	1.000	0.000	0.517	0.085	0.010	0.098	0.000	0.124	0.140	0.974
2000	1951	20000	0.332	0.525	0.079	0.007	0.077	0.029	0.006	0.176	1.231	0.000	0.766	0.128	0.010	0.098	0.000	0.159	0.140	1.301
5000	4878	5000	0.273	0.088	0.014	0.007	0.077	0.029	0.002	0.176	0.674	0.000	0.146	0.023	0.010	0.098	0.000	0.045	0.140	0.463
5000	4878	10000	0.279	0.130	0.021	0.007	0.077	0.029	0.002	0.176	0.730	0.000	0.207	0.034	0.010	0.098	0.000	0.059	0.140	0.539
5000	4878	20000	0.289	0.210	0.032	0.007	0.077	0.029	0.003	0.176	0.822	0.000	0.306	0.051	0.010	0.098	0.000	0.064	0.140	0.669
5000	4878	30000	0.298	0.273	0.041	0.007	0.077	0.029	0.003	0.176	0.904	0.000	0.394	0.067	0.010	0.098	0.000	0.074	0.140	0.783
5000	4878	40000	0.307	0.330	0.050	0.007	0.077	0.029	0.003	0.176	0.979	0.000	0.475	0.081	0.010	0.098	0.000	0.085	0.140	0.889
5000	4878	50000	0.315	0.386	0.058	0.007	0.077	0.029	0.004	0.176	1.051	0.000	0.552	0.094	0.010	0.098	0.000	0.096	0.140	0.990
10000	9756	5000	0.267	0.048	0.007	0.007	0.077	0.029	0.001	0.176	0.612	0.000	0.073	0.012	0.010	0.098	0.000	0.022	0.140	0.356
10000	9756	10000	0.270	0.070	0.010	0.007	0.077	0.029	0.001	0.176	0.640	0.000	0.103	0.017	0.010	0.098	0.000	0.025	0.140	0.393
10000	9756	20000	0.275	0.105	0.016	0.007	0.077	0.029	0.001	0.176	0.686	0.000	0.153	0.026	0.010	0.098	0.000	0.032	0.140	0.459
10000	9756	30000	0.280	0.136	0.020	0.007	0.077	0.029	0.001	0.176	0.727	0.000	0.197	0.033	0.010	0.098	0.000	0.037	0.140	0.516
10000	9756	40000	0.284	0.165	0.025	0.007	0.077	0.029	0.002	0.176	0.765	0.000	0.237	0.040	0.010	0.098	0.000	0.043	0.140	0.569
10000	9756	50000	0.288	0.193	0.029	0.007	0.077	0.029	0.002	0.176	0.800	0.000	0.276	0.047	0.010	0.098	0.000	0.048	0.140	0.619
10000	9756	60000	0.292	0.219	0.033	0.007	0.077	0.029	0.002	0.176	0.835	0.000	0.313	0.054	0.010	0.098	0.000	0.054	0.140	0.669
10000	9756	80000	0.299	0.270	0.041	0.007	0.077	0.029	0.003	0.176	0.901	0.000	0.384	0.066	0.010	0.098	0.000	0.065	0.140	0.764
10000	9756	100000	0.306	0.319	0.048	0.007	0.077	0.029	0.003	0.176	0.965	0.000	0.463	0.078	0.010	0.098	0.000	0.077	0.140	0.856
10000	9756	120000	0.313	0.367	0.055	0.007	0.077	0.029	0.003	0.176	1.027	0.000	0.528	0.089	0.010	0.098	0.000	0.088	0.140	0.946

TABLE 13 - NUCLEAR SUBMARINE GROUP MASS AND VOLUME FRACTIONS

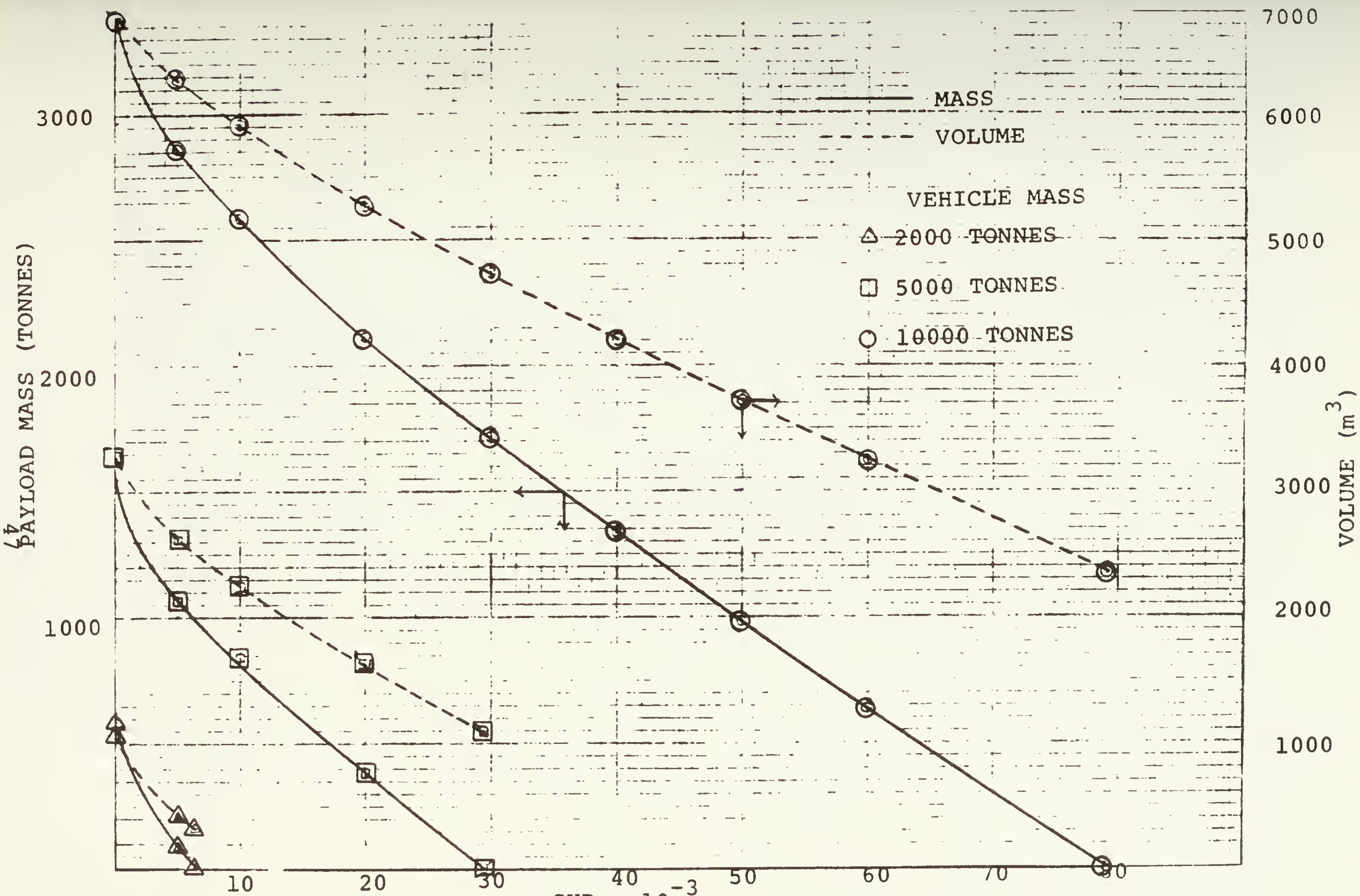


FIGURE 5 - NUCLEAR SUBMARINE PAYLOAD MASS AND VOLUME (m^3) vs. SHP

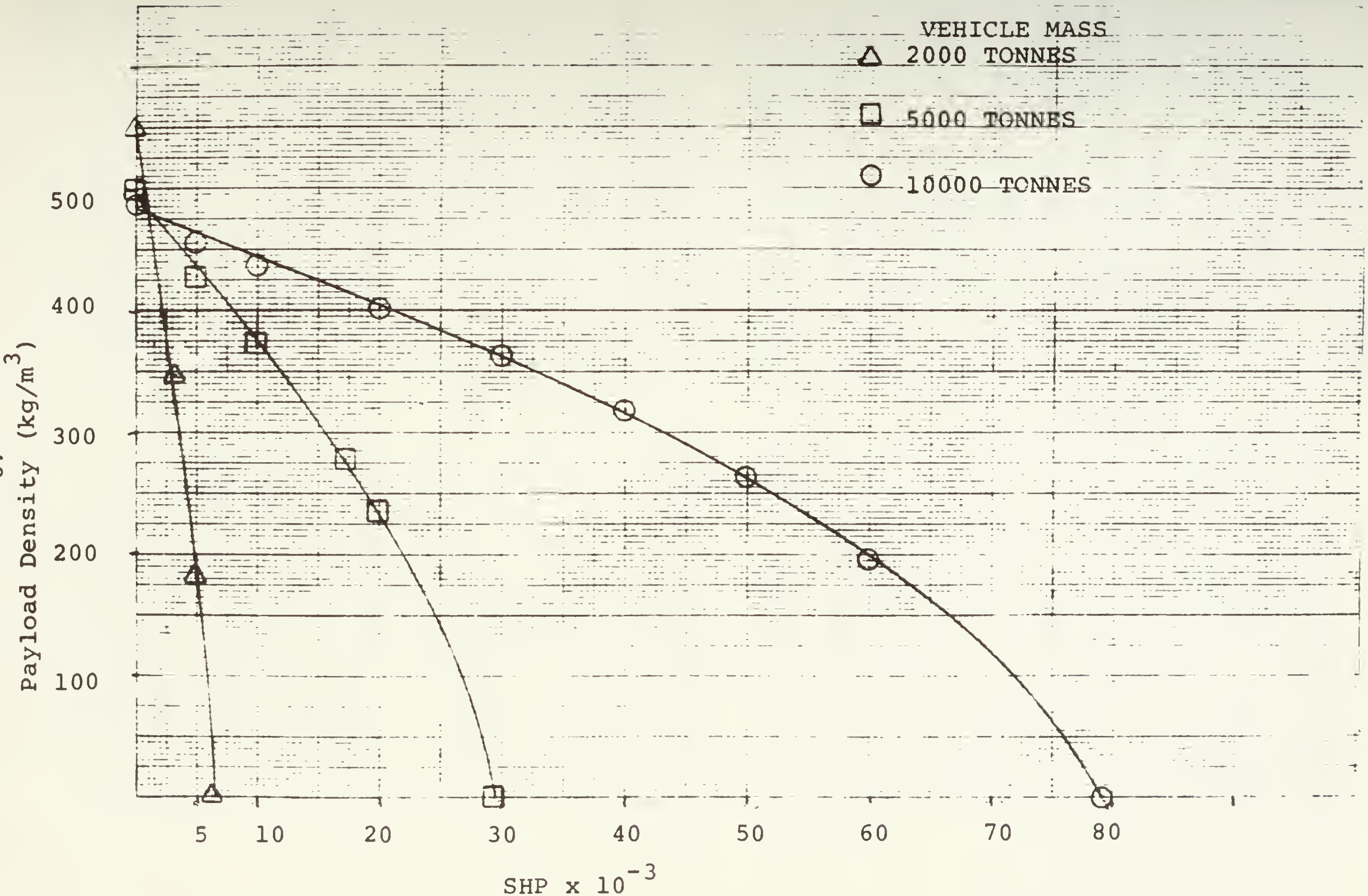


FIGURE 6 - NUCLEAR SUBMARINE PAYLOAD DENSITY vs. SHP, Δ

III.B. Fuel Cell Submarine

The results for the fuel cell submarine are presented in the same format as the nuclear submarine. The mass fractions and volume fractions are broken down by groups for each input submarine. (see Table 14) As with the nuclear submarine, a total mass fraction or volume fraction greater than one represents an infeasible design. Note that Table 14 does not include fuel and storage tank fraction. Without a specification of endurance, these items cannot be included. Therefore some of the remaining mass and volume would have to include this weight, at the cost of losing some payload. Again the effect of halving the operating depth is demonstrated in Table 14.

Figure 7 is a plot of payload mass and volume versus shaft horsepower at discrete vehicle masses and endurances. Since endurance is specified in Figures 7 through 12 and in Table 16, the payload mass and volume given in those figures already have fuel and storage tank mass and volume subtracted out. Figure 8 shows that a 1000 tonnes fuel cell submarine with 4000 NM endurance is infeasible at more than 5010 H.P. (26 kts), a 2000 tonnes submarine with the same endurance at 11,500 H.P. (30 kts), a 5000 tonnes submarine at 32,000 H.P. (35 kts) and a 10000 tonnes submarine at 69,000 H.P. (39 kts). Using the approach described for Figure 6, Figure 8 may be used to determine the feasibility of payload for fuel cell submarines.

TEST DEPTH = 400 METERS

			MASS FRACTION									VOLUME FRACTION								
DISPL	VOL	SHP	GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL	GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL
1000	976	5000	0.388	0.188	0.004	0.007	0.007	0.029	0.005	0.176	0.805	0.000	0.185	0.006	0.010	0.004	0.000	0.116	0.140	0.542
1000	976	10000	0.414	0.351	0.004	0.007	0.007	0.029	0.005	0.176	1.063	0.000	0.329	0.007	0.010	0.004	0.000	0.124	0.140	0.695
2000	1951	5000	0.378	0.104	0.002	0.007	0.007	0.029	0.002	0.176	0.705	0.000	0.100	0.004	0.010	0.004	0.000	0.058	0.140	0.406
2000	1951	10000	0.388	0.188	0.003	0.007	0.007	0.029	0.002	0.176	0.808	0.000	0.181	0.004	0.010	0.004	0.000	0.062	0.140	0.483
2000	1951	20000	0.414	0.348	0.003	0.007	0.007	0.029	0.003	0.176	1.048	0.000	0.326	0.005	0.010	0.004	0.000	0.077	0.140	0.643
5000	4878	5000	0.370	0.063	0.002	0.007	0.007	0.029	0.001	0.176	0.704	0.000	0.061	0.002	0.010	0.004	0.000	0.023	0.140	0.322
5000	4878	10000	0.375	0.095	0.002	0.007	0.007	0.029	0.001	0.176	0.742	0.000	0.090	0.003	0.010	0.004	0.000	0.025	0.140	0.352
5000	4878	20000	0.385	0.151	0.002	0.007	0.007	0.029	0.001	0.176	0.817	0.000	0.148	0.003	0.010	0.004	0.000	0.031	0.140	0.417
5000	4878	30000	0.394	0.217	0.002	0.007	0.007	0.029	0.001	0.176	0.892	0.000	0.206	0.003	0.010	0.004	0.000	0.034	0.140	0.479
5000	4878	40000	0.404	0.282	0.002	0.007	0.007	0.029	0.002	0.176	0.968	0.000	0.265	0.004	0.010	0.004	0.000	0.039	0.140	0.542
5000	4878	50000	0.413	0.348	0.002	0.007	0.007	0.029	0.002	0.176	1.043	0.000	0.323	0.004	0.010	0.004	0.000	0.042	0.140	0.603
10000	9756	5000	0.368	0.034	0.001	0.007	0.007	0.029	0.000	0.176	0.682	0.000	0.043	0.002	0.010	0.004	0.000	0.012	0.140	0.291
10000	9756	10000	0.370	0.051	0.001	0.007	0.007	0.029	0.000	0.176	0.701	0.000	0.058	0.002	0.010	0.004	0.000	0.012	0.140	0.307
10000	9756	20000	0.375	0.084	0.001	0.007	0.007	0.029	0.001	0.176	0.739	0.000	0.087	0.002	0.010	0.004	0.000	0.015	0.140	0.340
10000	9756	30000	0.380	0.117	0.001	0.007	0.007	0.029	0.001	0.176	0.777	0.000	0.117	0.002	0.010	0.004	0.000	0.017	0.140	0.371
10000	9756	40000	0.385	0.150	0.001	0.007	0.007	0.029	0.001	0.176	0.815	0.000	0.146	0.002	0.010	0.004	0.000	0.019	0.140	0.402
10000	9756	50000	0.389	0.183	0.002	0.007	0.007	0.029	0.001	0.176	0.853	0.000	0.175	0.002	0.010	0.004	0.000	0.021	0.140	0.433
10000	9756	60000	0.394	0.216	0.002	0.007	0.007	0.029	0.001	0.176	0.891	0.000	0.205	0.003	0.010	0.004	0.000	0.023	0.140	0.465
10000	9756	80000	0.404	0.282	0.002	0.007	0.007	0.029	0.001	0.176	0.966	0.000	0.263	0.003	0.010	0.004	0.000	0.027	0.140	0.528
10000	9756	100000	0.413	0.348	0.002	0.007	0.007	0.029	0.001	0.176	1.042	0.000	0.322	0.003	0.010	0.004	0.000	0.032	0.140	0.592

TEST DEPTH = 200 METERS

			MASS FRACTION									VOLUME FRACTION								
DISPL	VOL	SHP	GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL	GRP1	GRP2	GRP3	GRP4	GRP5	GRP6	PERS	BLST	TOTAL
1000	976	5000	0.288	0.188	0.004	0.007	0.007	0.029	0.005	0.176	0.763	0.000	0.185	0.006	0.010	0.004	0.000	0.116	0.140	0.542
1000	976	10000	0.312	0.351	0.004	0.007	0.007	0.029	0.005	0.176	0.951	0.000	0.329	0.007	0.010	0.004	0.000	0.124	0.140	0.695
1000	976	20000	0.388	0.678	0.005	0.007	0.007	0.029	0.006	0.176	1.327	0.000	0.618	0.008	0.010	0.004	0.000	0.155	0.140	1.016
2000	1951	5000	0.276	0.104	0.002	0.007	0.007	0.029	0.002	0.176	0.664	0.000	0.100	0.004	0.010	0.004	0.000	0.058	0.140	0.406
2000	1951	10000	0.288	0.188	0.003	0.007	0.007	0.029	0.002	0.176	0.758	0.000	0.181	0.004	0.010	0.004	0.000	0.062	0.140	0.483
2000	1951	20000	0.312	0.348	0.003	0.007	0.007	0.029	0.003	0.176	0.946	0.000	0.326	0.005	0.010	0.004	0.000	0.077	0.140	0.643
2000	1951	30000	0.336	0.513	0.004	0.007	0.007	0.029	0.003	0.176	1.134	0.000	0.471	0.006	0.010	0.004	0.000	0.085	0.140	0.797
5000	4878	5000	0.268	0.063	0.002	0.007	0.007	0.029	0.001	0.176	0.602	0.000	0.061	0.002	0.010	0.004	0.000	0.023	0.140	0.322
5000	4878	10000	0.274	0.095	0.002	0.007	0.007	0.029	0.001	0.176	0.640	0.000	0.090	0.003	0.010	0.004	0.000	0.025	0.140	0.352
5000	4878	20000	0.283	0.151	0.002	0.007	0.007	0.029	0.001	0.176	0.716	0.000	0.148	0.003	0.010	0.004	0.000	0.031	0.140	0.417
5000	4878	30000	0.293	0.217	0.002	0.007	0.007	0.029	0.001	0.176	0.791	0.000	0.206	0.003	0.010	0.004	0.000	0.034	0.140	0.479
5000	4878	40000	0.302	0.282	0.002	0.007	0.007	0.029	0.002	0.176	0.866	0.000	0.265	0.004	0.010	0.004	0.000	0.039	0.140	0.542
5000	4878	50000	0.312	0.348	0.002	0.007	0.007	0.029	0.002	0.176	0.942	0.000	0.323	0.004	0.010	0.004	0.000	0.042	0.140	0.603
5000	4878	60000	0.321	0.413	0.003	0.007	0.007	0.029	0.002	0.176	1.017	0.000	0.381	0.004	0.010	0.004	0.000	0.046	0.140	0.666
10000	9756	5000	0.266	0.034	0.001	0.007	0.007	0.029	0.000	0.176	0.580	0.000	0.043	0.002	0.010	0.004	0.000	0.012	0.140	0.291
10000	9756	10000	0.268	0.051	0.001	0.007	0.007	0.029	0.000	0.176	0.598	0.000	0.058	0.002	0.010	0.004	0.000	0.012	0.140	0.307
10000	9756	20000	0.273	0.084	0.001	0.007	0.007	0.029	0.001	0.176	0.637	0.000	0.087	0.002	0.010	0.004	0.000	0.015	0.140	0.340
10000	9756	30000	0.278	0.117	0.001	0.007	0.007	0.029	0.001	0.176	0.675	0.000	0.117	0.002	0.010	0.004	0.000	0.017	0.140	0.371
10000	9756	40000	0.283	0.150	0.001	0.007	0.007	0.029	0.001	0.176	0.713	0.000	0.146	0.002	0.010	0.004	0.000	0.019	0.140	0.402
10000	9756	50000	0.288	0.183	0.002	0.007	0.007	0.029	0.001	0.176	0.751	0.000	0.175	0.002	0.010	0.004	0.000	0.021	0.140	0.433
10000	9756	60000	0.293	0.216	0.002	0.007	0.007	0.029	0.001	0.176	0.789	0.000	0.205	0.003	0.010	0.004	0.000	0.023	0.140	0.465
10000	9756	80000	0.302	0.282	0.002	0.007	0.007	0.029	0.001	0.176	0.865	0.000	0.263	0.003	0.010	0.004	0.000	0.027	0.140	0.528
10000	9756	100000	0.312	0.348	0.002	0.007	0.007	0.029	0.001	0.176	0.941	0.000	0.322	0.003	0.010	0.004	0.000	0.032	0.140	0.592
10000	9756	120000	0.321	0.414	0.003	0.007	0.007	0.029	0.001	0.176	1.017	0.000	0.381	0.004	0.010	0.004	0.000	0.036	0.140	0.655

TABLE 14 - FUEL CELL SUBMARINES MASS AND VOLUME FRACTIONS

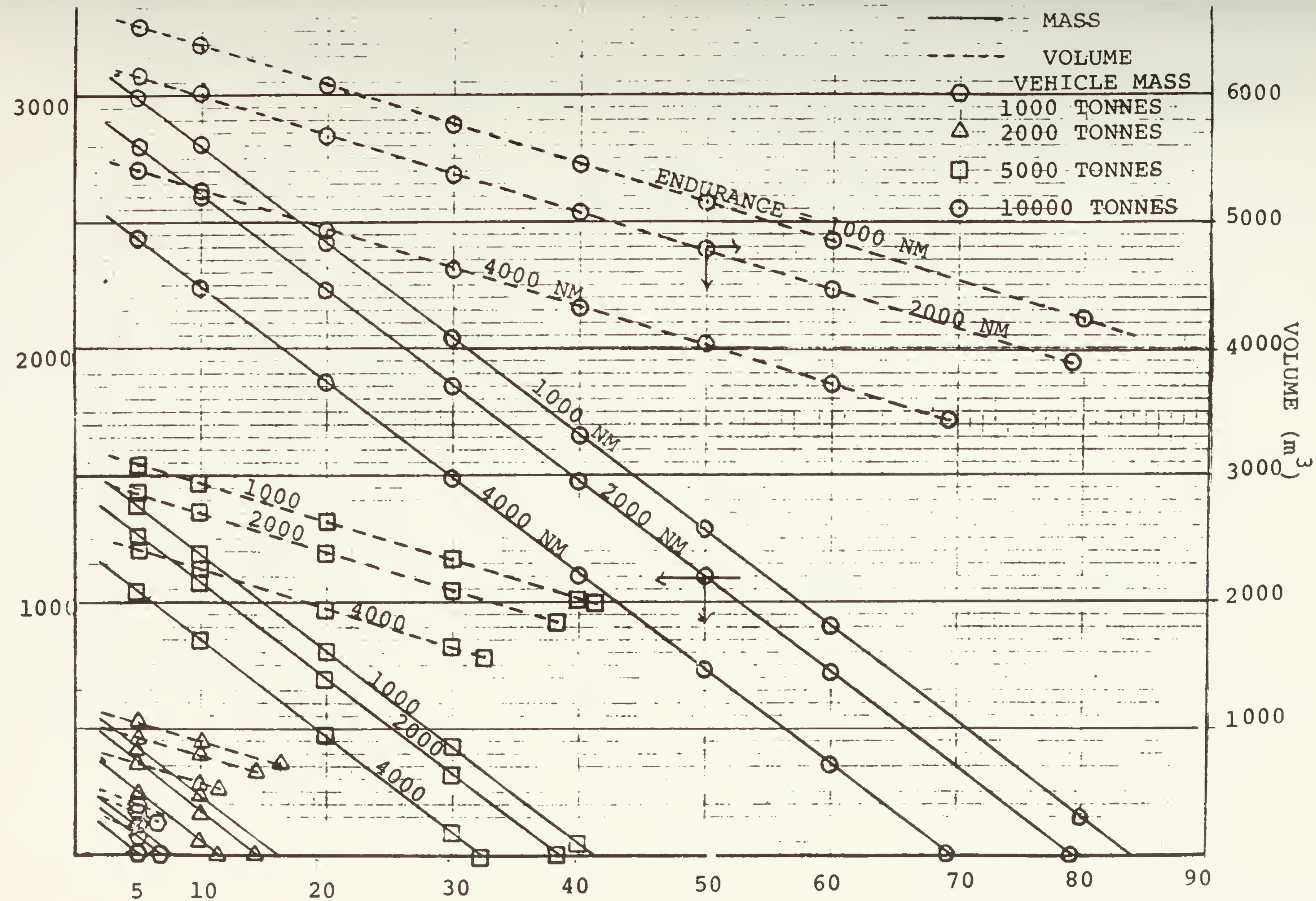


FIGURE 7 - FUEL CELL SUBMARINE PAYLOAD MASS AND VOLUME vs. SHP, Δ, ENDURANCE

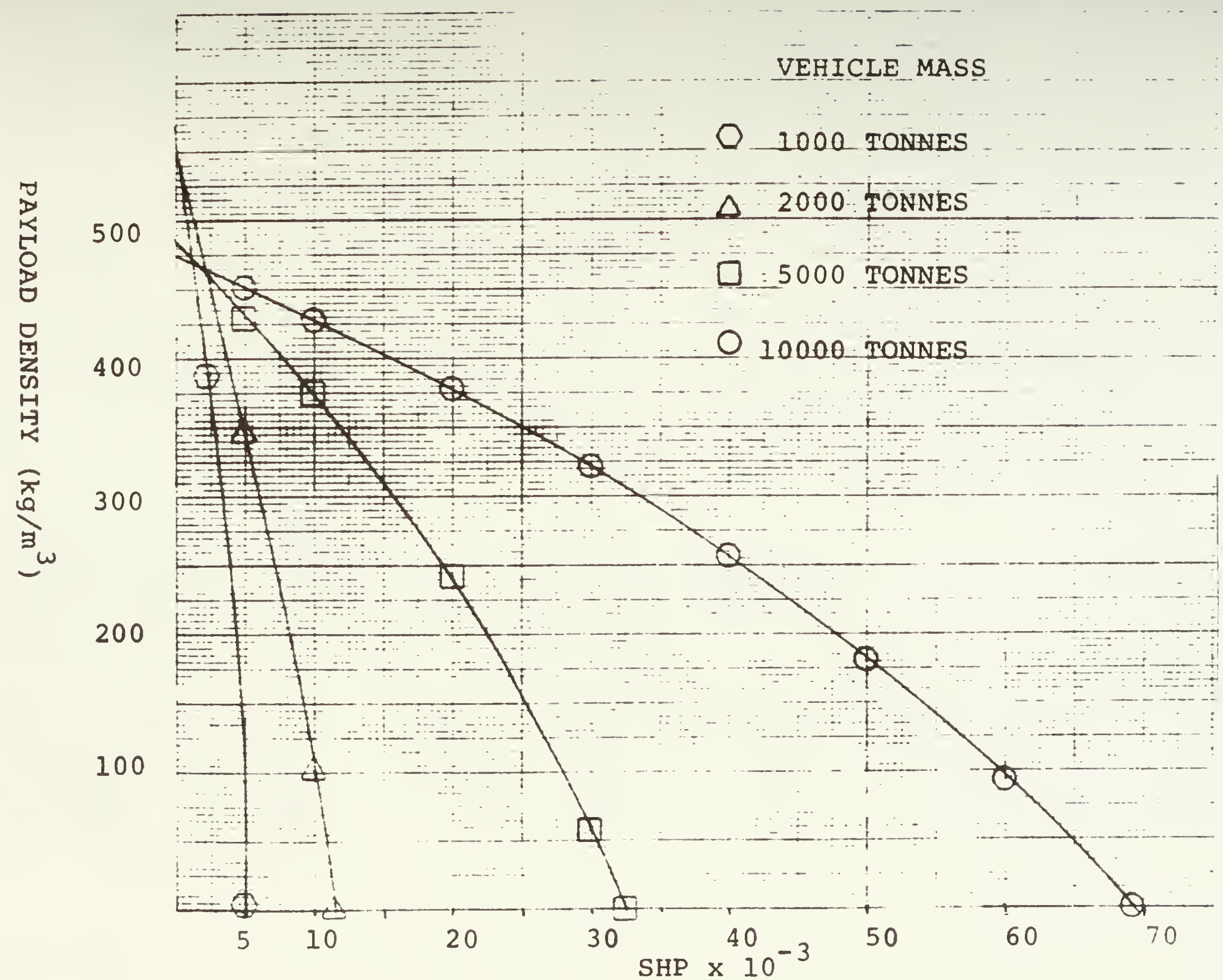


FIGURE 8 - PAYLOAD DENSITY vs. SHP FUEL CELL SUBMARINE WITH 4000 NM ENDURANCE

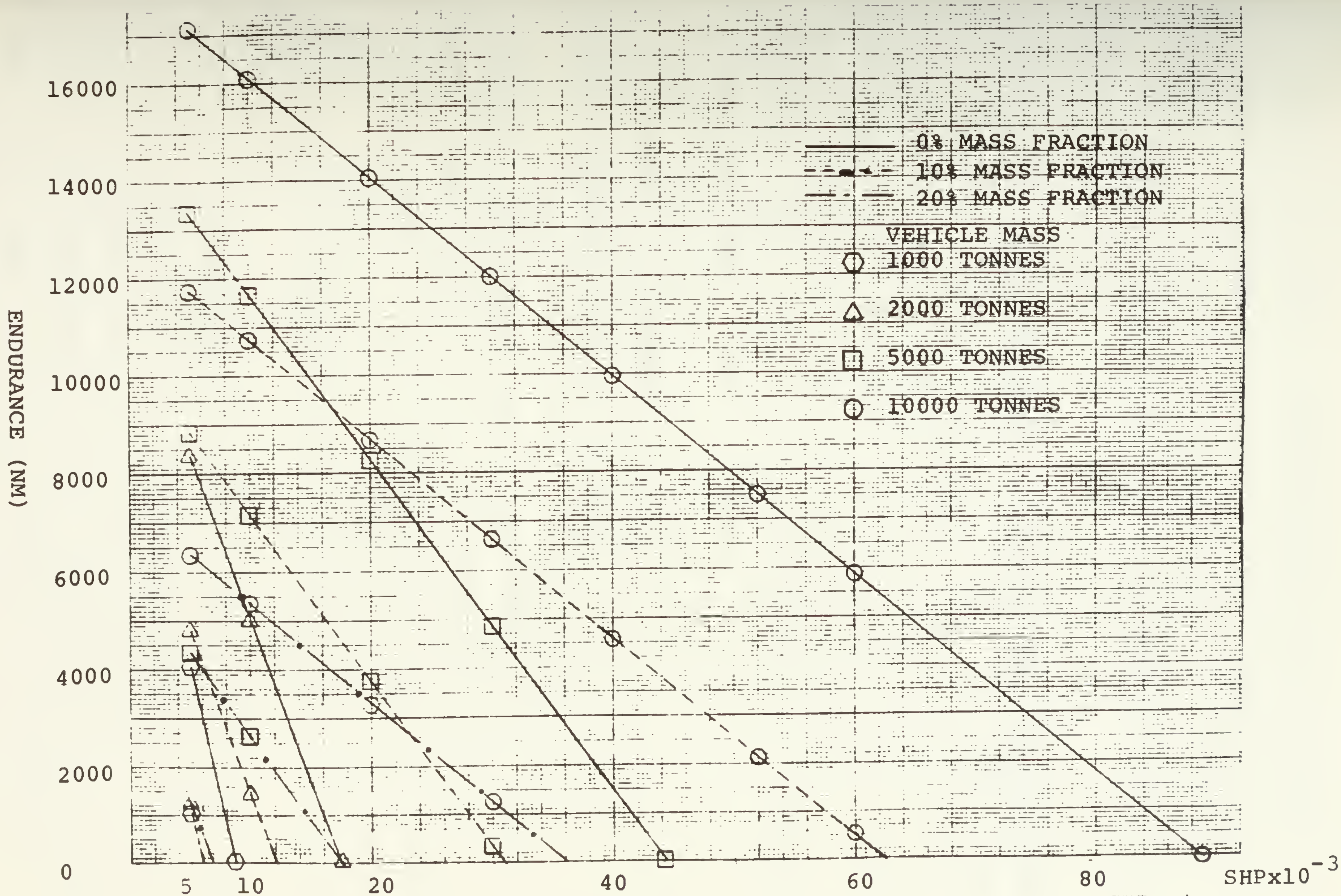


FIGURE 9 - FUEL CELL SUB ENDURANCE AT DISCRETE PAYLOAD MASS FRACTIONS vs. SHP, Δ

Figure 9 is added to demonstrate the effect of shaft horsepower, displacement and payload mass fraction on the endurance of a fuel cell powered submarine.

No submarine was infeasible based on vertical center of gravity requirements.

III.C. Comparison of Nuclear Reactor and Fuel Cell Submarines

Table 15 lists the maximum velocity for a given shaft horsepower and size. Maximum velocity is not a function of power plant type. In addition, Table 15 lists the cost data for each power plant. The lack of an entry represents an infeasible design. This data is incorporated into figures in the assessment section which follows.

III.D. Results of Assessment Methods

III.D.1. Maximum Velocity Assessment

Figures 10, 11, and 12 are the results of the assessment method which looked at maximum feasible velocity based on vehicle size, power, endurance, and payload mass fraction. The fuel cell submarine data was from calculations based on 2000 NM and 4000 NM endurance ranges. These figures demonstrated the maximum velocity each particular submarine can achieve.

Table 16 summarizes the results from Figures 10-12. It is evident from Table 16 that at small submarine sizes, the fuel cell submarine can achieve higher speeds than a nuclear submarine at respectable values of endurance and carrying the same payload mass as the nuclear submarine. An example of

TABLE 15

Maximum Velocities and Capital Costs for the Nuclear Submarine and Fuel Cell Submarine with 4000 NM Endurance and No Payload

Vehicle Mass (tonnes)	Shaft Horse-power (HP)	Max. Vel. (knots)	Nuc. Cost ($1976\$ \times 10^{-6}$)	Fuel Cell Cost ($1976\$ \times 10^{-6}$)
1000	5000	26.2	--	25.1
2000	5000	22.4	54.3	34.0
2000	10000	28.5	--	39.5
5000	5000	18.4	71.2	53.4
5000	10000	23.3	84.3	58.8
5000	20000	29.5	105.9	69.6
5000	30000	34.0	--	80.4
10000	5000	15.8	92.4	77.7
10000	10000	20.0	105.4	83.1
10000	20000	25.4	127.0	93.8
10000	30000	29.2	145.9	104.6
10000	40000	32.2	163.5	115.4
10000	50000	34.8	180.1	126.2
10000	60000	37.0	196.2	136.9

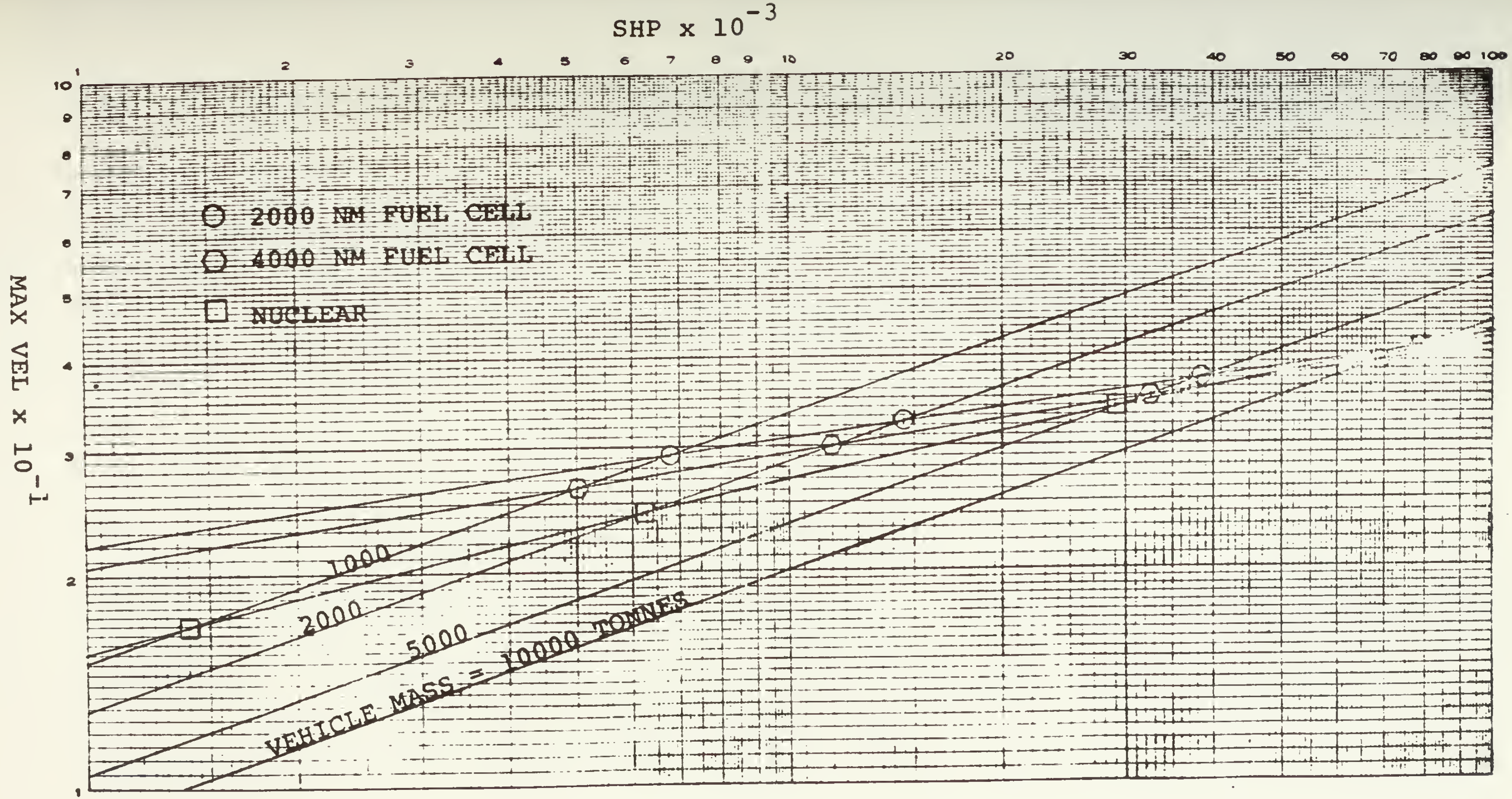


FIGURE 10 - FEASIBILITY LIMIT FOR 0% PAYLOAD MASS FRACTION: MAX. VELOCITY vs. SHP, Δ FOR 2000 NM, 4000 NM FUEL CELL SUBMARINE AND NUCLEAR SUBMARINE

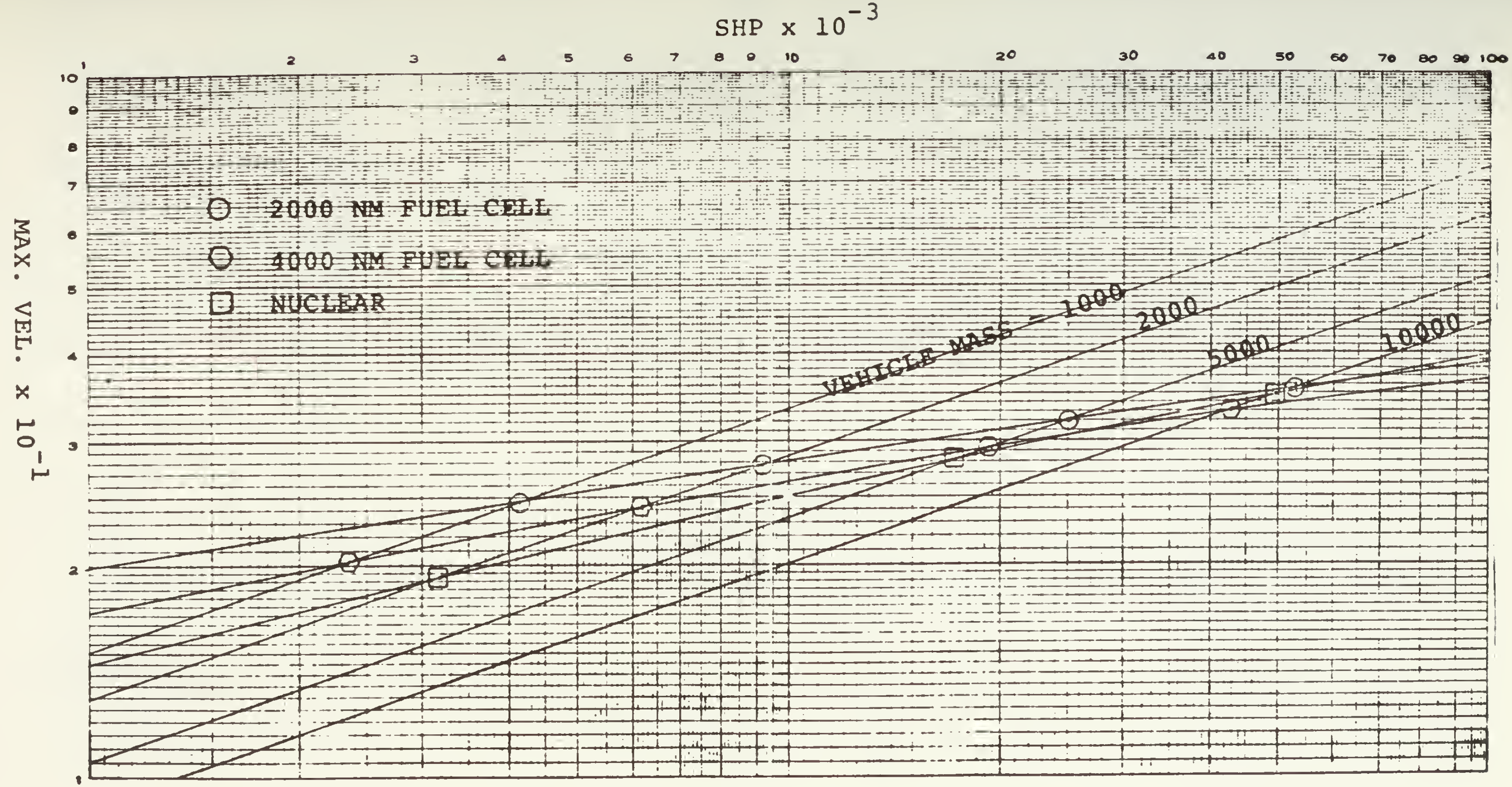


FIGURE 11 - FEASIBILITY LIMIT FOR 10% PAYLOAD MASS FRACTION: MAX. VELOCITY vs. SHP,

Δ FOR 2000 NM, 4000 NM FUEL CELL SUBMARINE, AND NUCLEAR SUBMARINE

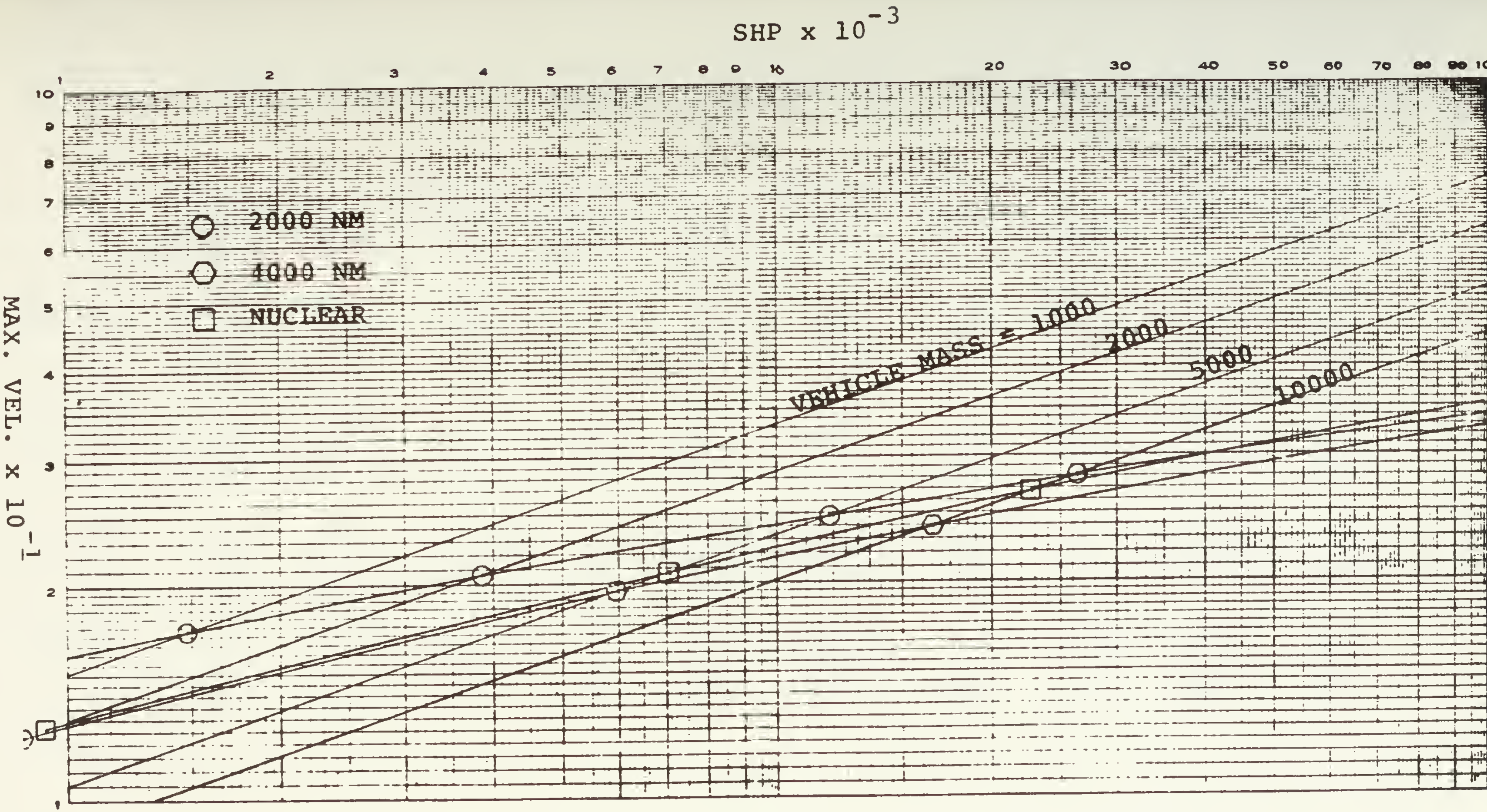


FIGURE 12 - FEASIBILITY LIMIT FOR 20% PAYLOAD MASS FRACTION: MAX. VELOCITY vs. SHP, Δ FOR A 2000 NM, 4000 NM FUEL CELL SUBMARINE, AND A NUCLEAR SUBMARINE

TABLE 16 - MAXIMUM FEASIBLE VELOCITIES OF SUBMARINES, AND PAYLOAD VOLUME AND DENSITY AS A FUNCTION OF VEHICLE MASS, PAYLOAD MASS FRACTION, POWER PLANT TYPE AND ENDURANCE

		NUCLEAR			2000 NM FUEL CELL			4000 NM FUEL CELL		
	PAYLOAD MASS FRACTION	Y_{max} (Knots)	PAYLOAD VOLUME (m^3)	PAYLOAD DENSITY (kg/m^3)	Y_{MAX} (Knots)	PAYLOAD VOLUME (m^3)	PAYLOAD DENSITY (kg/m^3)	Y_{max} (Knots)	PAYLOAD VOLUME (m^3)	PAYLOAD DENSITY (kg/m^3)
1000	0.0	17.0	44.3	0	29.1	259.1	0	26.2	174.2	0
	0.1	----	-----	---	24.6	342.2	292	20.2	256.9	389
	0.2	----	-----	---	17.3	417.8	479	----	-----	---
2000	0.0	24.2	317.3	0	32.3	654.4	0	29.9	512.0	0
	0.1	19.2	579.1	346	27.7	812.8	246	24.2	670.3	298
	0.2	12.6	841.3	475	20.5	971.5	412	12.3	829.0	483
5000	0.0	33.7	1099.8	0	37.0	1847.9	0	34.9	1574.0	0
	0.1	28.1	1790.8	279	31.9	2241.2	223	29.2	1989.2	251
	0.2	20.7	2461.1	406	24.7	2656.7	376	19.5	2382.6	420
10000	0.0	40.7	2355.5	0	40.7	3892.8	0	38.9	3437.3	0
	0.1	34.6	3745.9	267	35.4	4696.7	213	33.0	4241.2	236
	0.2	26.7	5114.8	391	27.9	5500.9	363	23.8	5060.4	395

this is the 2000 tonnes submarine with a payload mass of 200 tonnes, (10% payload mass fraction). The maximum velocity of this submarine with a nuclear plant is 19.3 kts whereas with a fuel cell, the submarine can achieve 27.7 kts at 2000 NM endurance and 24.2 kts at 4000 NM endurance. Referring to Table 16, the latter submarine has volume available for payload equal to 670 m^3 and the nuclear submarine has volume for payload equal to 579 m^3. Referring ahead to Figure 14, the 2000 tonnes nuclear submarine should cost on the order of \$48,500,000 in 1976 dollars (without payload) whereas the 2000 tonnes, 4000 NM fuel cell submarine should cost on the order of \$35,000,000. Clearly the 4000 NM fuel cell submarine is an attractive competitor to the nuclear submarine in the 2000 tonnes size. Its advantages are that it is five knots faster, has greater payload volume and costs 38% less. Its disadvantage is that it has 4000 NM endurance instead of 60 days x 19.3 knots x 24 hrs/day = 27,500 NM.

On the other hand, at 5000 tonnes some of the advantages of the fuel cell submarine fade. With a payload mass equal to 500 tonnes (10% payload mass fraction), it has only a one knot advantage over the nuclear submarine, its payload volume is constrained to 1989 m^3 and compared to 1791 m^3 for the nuclear submarine, and its cost without payload is about \$69,000,000 as compared to about \$100,000,000 for the nuclear submarine. At 10000 tonnes it is two knots slower than the nuclear submarine for the payload mass of 1000 tonnes, (payload mass fraction 10%), its payload volume is constrained to less

than 4241 m^3 as compared to 3746 m^3 for the nuclear submarine and its cost without payload is $119,000,000 compared to $179,000,000 for the nuclear submarine. Clearly the case for fuel cell submarines is less strong at large sizes than at small sizes as controlled by the constraints of this study.

III.D.2. Capital Cost Assessment

Figure 13 plots cost versus shaft horsepower for discrete vehicle masses. Figure 14 plots maximum velocity versus cost. In both figures the fuel cell submarine shows a clear cost advantage. Data was added for smaller submarines with power outputs below 5000 H.P. to give a clearer picture in the lower power region.

It is evident from Figure 14 that at the $70,000,000 cost of a 5000 tonnes, 29 knot, 4000 NM endurance, and 500 tonnes (1950 m^3) payload fuel cell submarine (not including payload costs), a nuclear submarine of the same size is feasible that has 5000 installed horsepower instead of 20,000 with a speed of 17.5 knots instead of 29 kts. According to Figure 5, this submarine could carry 1122 tonnes of payload with 2619 m^3 available for payload volume. Clearly this submarine would be much more attractive for limited speed missions than the fuel cell submarine.

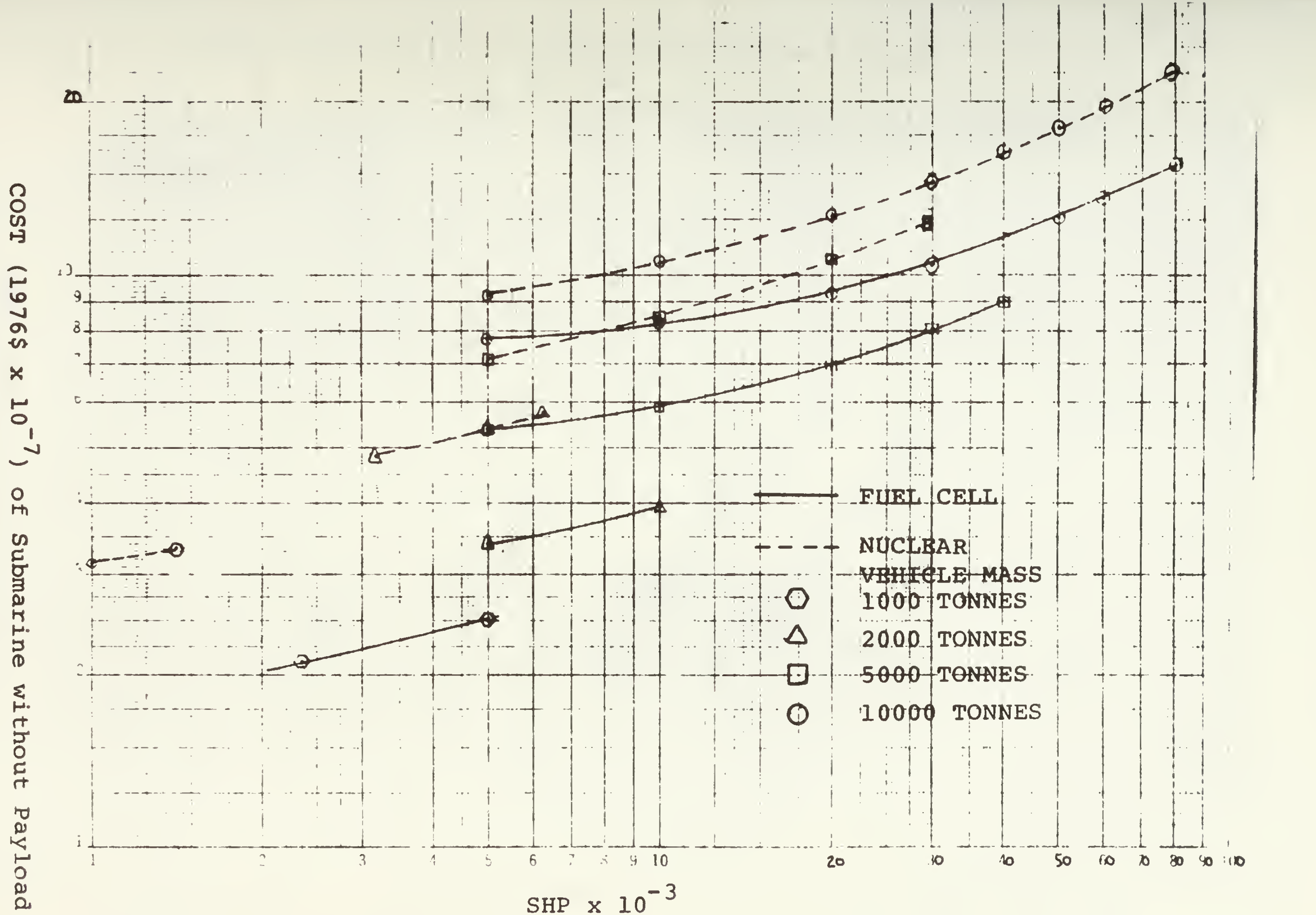


FIGURE 13 - CAPITAL COSTS vs. SHP, Δ: NUCLEAR SUBMARINE AND 4000 NM ENDURANCE SUBMARINE

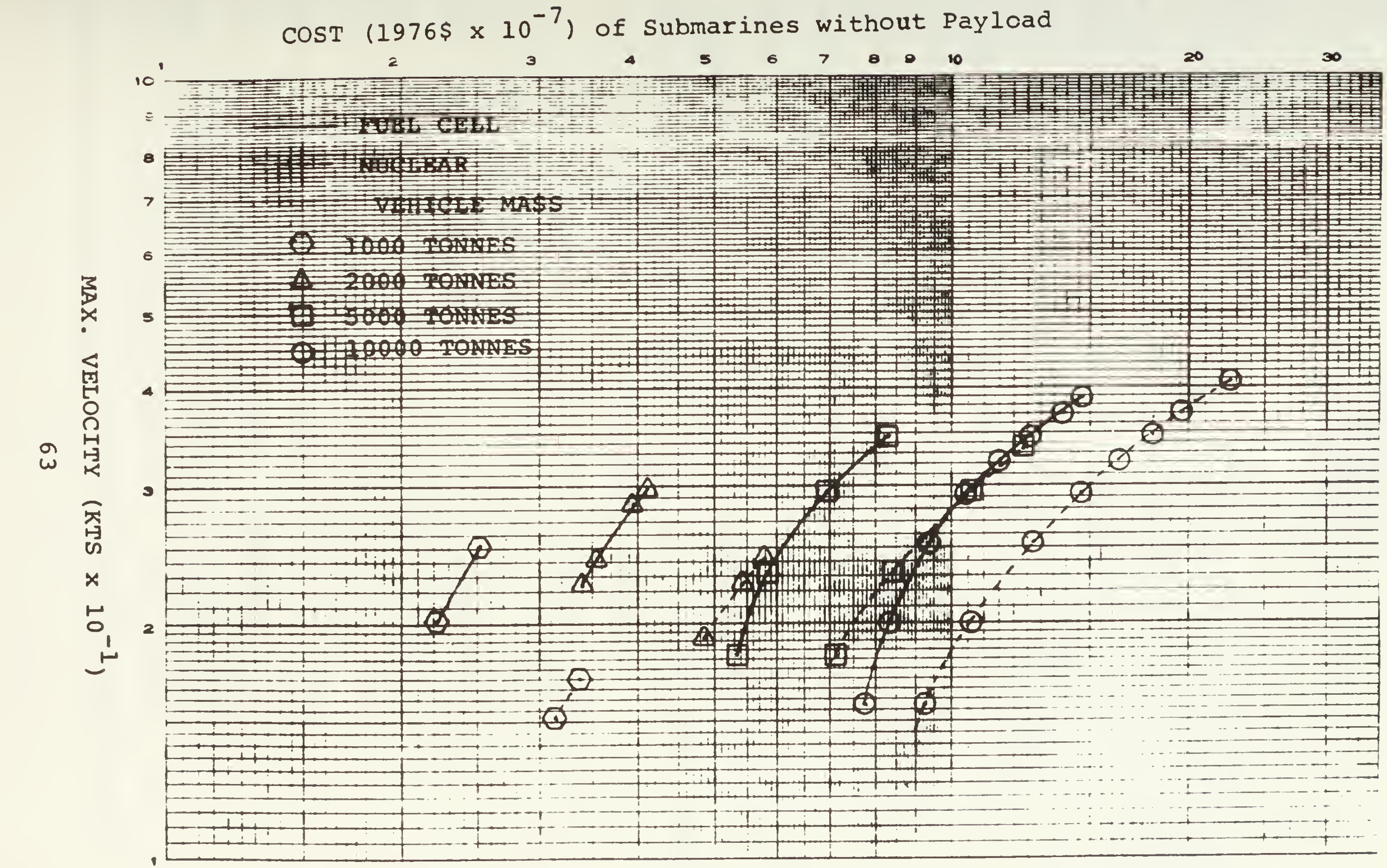


FIGURE 14 - CAPITAL COSTS FOR NUCLEAR SUBMARINE AND 4000 NM ENDURANCE FUEL CELL SUBMARINE vs. MAX. VELOCITY

CHAPTER IV

DISCUSSION

IV.A. Nuclear Reactor

U.S. Navy nuclear powered submarines are divided into two groups, attack submarines and ballistic missile carrying submarines. Traditionally, attack submarines have carried about a 10% payload mass fraction and ballistic missile submarines about a 17-20% payload mass fraction. Therefore the feasibility limits in Figures 11 and 12 are close to actual submarines. The limits for a 0% payload mass fraction are not precise due to the requirement for personnel to drive the submarine and the sensors needed to do that. These items are considered part of the payload. Figure 11 can be used to predict the necessary shaft horsepower and/or displacement to drive a submarine at a required velocity.

Table 13 gives evidence of the penalty one pays for increasing the maximum operating depth. The effect of decreasing the operating depth by 1/2 from 400 meters to 200 meters reduced the hull mass fraction by approximately 10%. This margin can be directly taken up by the payload. Note however, that the volume margins did not change, based on the convention used in this study. Therefore, the density of the payload would increase by decreasing depth, having the effect of raising the lines in Figure 8. As a result, for a given payload and vehicle mass, a submarine will become weight

limited at a greater shaft horsepower. As a result, as the maximum operating depth increases, a submarine increases its chance of being weight limited.

IV.B. Fuel Cell

The fuel cell submarine had one additional parameter affecting its design, namely endurance. The effect of endurance on the payload fractions and the effect of payload mass fractions on endurance are shown in Figures 7 and 9 respectively. Both of these figures demonstrate the penalty endurance inflicts on the payload. Figure 8 is plotted using an endurance of 4000 NM. Lowering the endurance would move the curves in this figure to the right, thereby lowering the shaft horsepower at which the submarine will shift from being volume limited to mass limited for a given payload.

For the same reasons mentioned in the previous section, the 10% and 20% payload mass fractions are the realistic numbers. The fuel cell submarine has identical constraints as the nuclear powered submarine. Changing the maximum operating depth of the fuel cell submarine has the same effect as it did on the nuclear submarine.

IV.C. Comparison of Nuclear Reactor and Fuel Cell Submarines

The differences between payload carrying capabilities of the nuclear powered submarine and fuel cell submarine are small in the middle region of this study. Fuel cell submarines have greater payload carrying capabilities at smaller vehicle

masses. Nuclear powered submarines are infeasible at the lowest vehicle mass, due to the high penalty paid for the reactor plant and the necessary shielding. This penalty is relatively less at larger vehicle masses.

On the other end of the scale, nuclear powered reactors offer similar or better payload carrying capabilities at higher shaft horsepower and vehicle masses. The fuel cell main propulsion mass is based on a linear approximation, while the nuclear reactor is not. Therefore the fuel cell does not show any improvement in specific weight at large power outputs. Realistically, the fuel cell should show some improvement with increasing power outputs but just how much is not known. The specific weight was fixed at 35 lb/KW rather than introduce an arbitrary number. If the fuel cell has a greater specific weight at larger power outputs, the payload carrying advantage evident at low shaft horsepower and vehicle masses would also be maintained throughout the input range.

The fuel cell submarine has a clear advantage over the nuclear powered submarine based on cost. Figures 13 and 14 show that the fuel cell submarine is more than 20% cheaper throughout the input range. As stated in the Math Model Section, the cost for the fuel cell was estimated at $500/KW. The effect of doubling this cost would be to raise the cost of the fuel cell submarine up to the level of the nuclear submarine, and even surpass it at high shaft horsepower.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Within the constraints and parameters used in this study the fuel cell powered submarine offers better or equal payload carrying capabilities at a substantially lower cost. The nuclear powered submarine has the advantage of a much higher endurance limit, only limited by personnel requirements. The U.S. Navy has not changed the basic design of the pressurized water nuclear reactor for twenty years.

The fuel cell powered submarine will require substantial studying before it can be built. A specific fuel cell would have to be designed. This fuel cell would be many times larger than the one designed for the Space Shuttle. By taking into account its intended use, specific characteristics would change. Possibly the specific weight and volume will be lower. Its life would definitely have to be improved before it will be used in submarines. The propulsion motor offers another chance for improvements. Superconducting motors have been designed which will lower the weight and volume of the motor and improve its efficiency. The improvement in efficiency alone should extend endurance ranges of the fuel cell submarine another 5%. The fuel storage problem will have to be reevaluated for the specific design. Metal hydride storage of hydrogen may prove to be safer and better than cryogenic storage. Personnel will have to be trained plus repair and maintenance facilities have to be designed. Given

a similar effort as the nuclear power program received in the 1950's, the fuel cell powered submarine could replace nuclear powered submarines in some mission areas.

The fuel cell powered submarine can never totally replace nuclear powered submarines. There are many missions where endurances at high speeds are necessary. However, there are some missions where the fuel cell powered submarine can do the job at much lower costs.

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APPENDIX I

RESISTANCE AND POWERING CALCULATIONS (Ref 10)

$SHP = k \ \Delta^{2/3} \ (y)^3$

Δ in LTONS

y in knots

INPUTS $L/D = 9$

$\Delta C_f = 0.0004$

D = 19.1 ft., 21.1, 32.7, 41.1

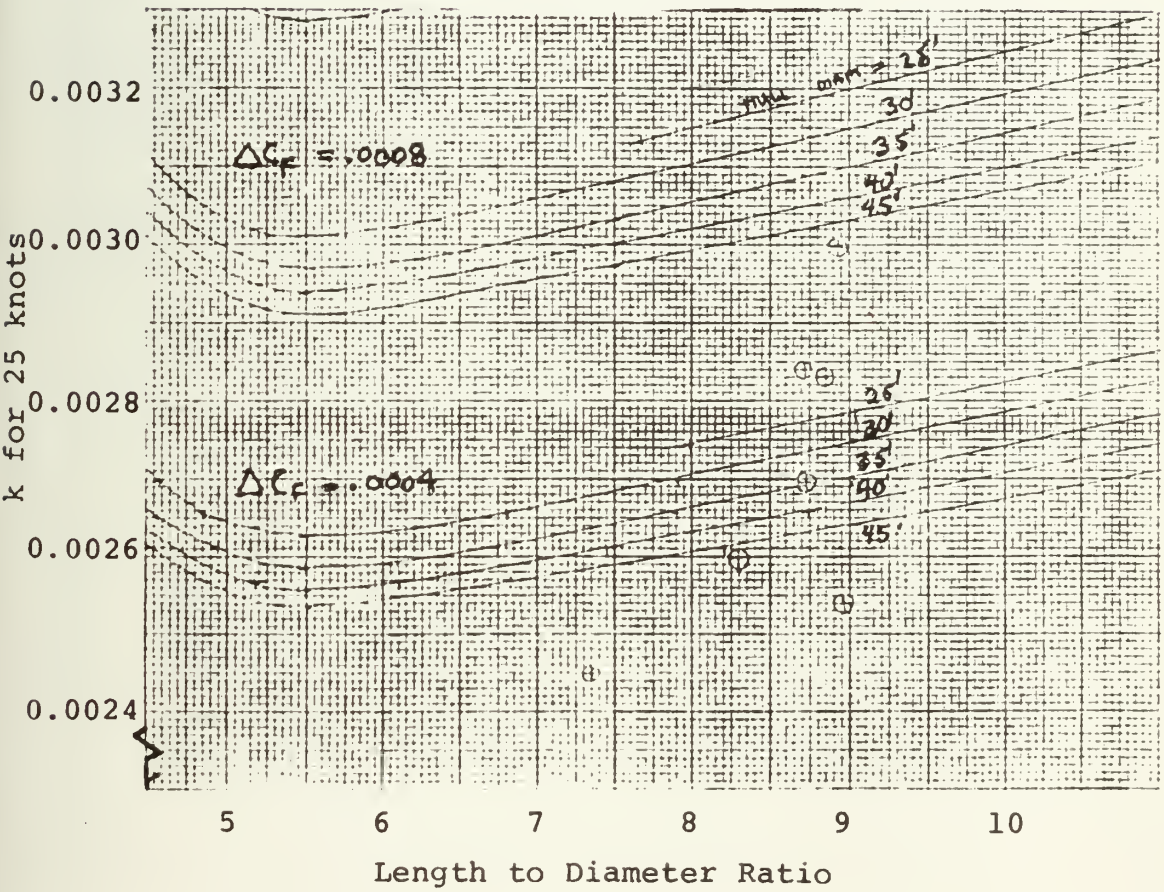

FIGURE 15 - Powering Coefficient k for 25 knots (ref. 10)

VEHICLE MASS	DIAMETER	k
1000	19.1	0.002825
2000	24.1	0.00279
5000	32.7	0.00272
10000	41.1	0.002665

Since k is based on a 25 KT submarine, a factor P9 is used to correct for submarine velocity. (See Figure 17)

The equation used to estimate Figure 17 is:

$$P9 = 1 + 0.2 \ LOG_{10} \ (25/y)$$

$$k = P9 \cdot k_{25kts}.$$

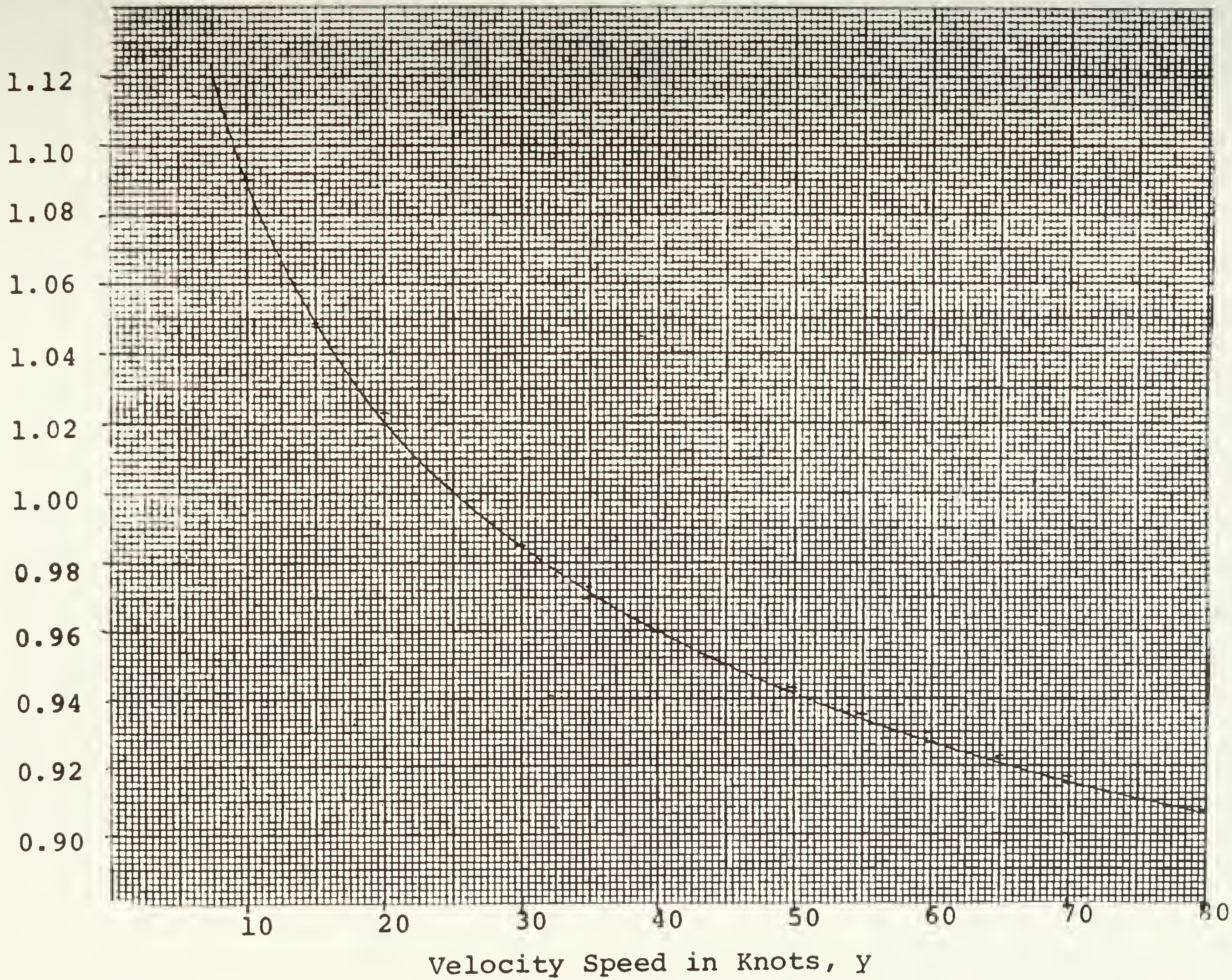

FIGURE 16 - SPEED CORRECTION FACTOR P9 vs. VELOCITY, y (Ref. 10)

APPENDIX II

FUEL CELL SHAFTING AND PROPELLER CALCULATIONS (Ref 10)

INPUTS	VEHICLE MASS	DIAMETER (ft)	LENGTH SHAFT
	1000	12.73	34.4
	2000	16.04	43.3
	3000	21.77	58.8
	10000	27.43	74.1

Propeller Equations - fully submerged fixed pitch partially cavitating propeller

Weight = 6.5 x $(\text{diameter})^3$ (lbs)

RPM = $\{50 \times [(\text{SHP})^{0.2}/(1.02 \times \text{diameter})]\}^{5/3}$

Shafting Equations -

Intermediate Shafting

$$D_o = \left[\frac{16T}{\pi S_s} \times \frac{1}{(1-\zeta^4)}\right]^{1/3} = \text{Shaft outer diameter - inches [4.14]}$$

T = Design Torque - lb x in

S_s = Shear stress due to torsion taken at 10,000 lb/in^2 - lb/in^2

$\zeta = D_i/D_o = 0.1098 \text{ Log}_{10}T + 0.2999$

(Based on linear approximation to minimum shaft weight, per figure 15 of [4.14])

$\zeta \leq 0.98$

D_i = Shaft inner diameter - inches

$L^2_{max} = \frac{6\pi\ D_o}{n} \sqrt{\frac{gE}{\rho_s}(1+\zeta^2)}$ = Max shaft segment length - inches [4.14] (To insure operation below 1st critical speed)

n = rotational speed - rpm

g = acceleration of gravity - 386 in/sec^2

E = Young's Modulus - 30×10^6 lb/in^2

ρ_s = density of steel - .283 lb/in^3

Propeller Shafting

same as above except:

$\zeta \leq 0.67$

Intermediate and Propeller Shafting

$W_{c\&m}$ = coupling, bearing, lubrication and miscellaneous weights per shaft segment - lbs

$= 6.6 \times 10^{-4} \times T + 5 \times D_o \quad \times L/12$ [4.14]

L = shaft segment length - inches

$W_{shaft} = .283 \times \frac{\pi}{4} \times (D_o^2 - D_i^2) \times L$

Fuel Cell Group 2 Shafting and Propeller Weight

VEHICLE MASS	EQUATION	
1000	W(1) = 0.0001964 [SHP] + 9.43	
2000	W(2) = 0.0002532 [SHP] + 18.15	in (TONNES)
5000	W(3) = 0.0003451 [SHP] + 44.00	
10000	W(4) = 0.0005436 [SHP] + 82.30	

APPENDIX III - LISTING OF NUCLEAR SUBMARINE PROGRAM

```
10 N=1
20 INPUT O
30 DIM D[4],S[15]
40 FOR I=1 TO 15
50 READ S[I]
60 NEXT I
70 D[1]=1000
80 D[2]=2000
90 D[3]=5000
100 D[4]=10000
110 K[1]=0.002825
120 K[2]=0.00279
130 K[3]=0.00272
140 K[4]=0.002665
150 FOR K=1 TO 15
160 FOR L=N TO 4
170 S1=S[K]*1000
180 X=D[L]/1.025
190 V=(S1/(K[L]*((D[L]*0.9842)^(2/3))))^(1/3)
200 P9=(1+0.2*LGT(25/X))
210 V=V/(P9^(1/3))
220 WRITE (0,230)S1,D[L],X,V
230 FORMAT /,/,1X,"SHP=",F7.0,2X,"DISPL=",F6.0,2X,"VOL=",F9.1,2X,"VEL=",F6.2
240 W2=4.462*(S1^0.5)+0.017*S1
250 W1=W2*0.1451+D[L]*0.3628
260 W1=0
270 T1=W1*0.4953
280 H1=13800*((W1*0.9842)^0.57)
290 M1=220302.4*((W1*0.9842)^0.41)
300 W2=(48.28*W2+5865)*0.02832
310 W2=W2+79.96
320 T2=W2*0.4505
330 H2=W2*679.1
340 M2=W2*4488.4
350 W3=W2*0.15
```

```
360 U3=V3*1.587
370 T3=V3*0.5371
380 H3=V3*670.1
390 M3=V3*4458.4
400 V4=D[L]*0.0066
410 U4=V4*1.516
420 T4=V4*0.75
430 H4=((V4*0.0842)^0.76)*5080
440 M4=V4*10012.5
450 V5=D[L]*0.0771
460 U5=V5*1.239
470 T5=V5*0.5379
480 H5=((V5*0.0842)^0.52)*30130
490 M5=((V5*0.0842)^0.50)*161368
500 N1=INT(20+(S1/1500))
510 N3=INT((S1/20000)^(0.5))+3
520 N2=INT(S1/20000)+2
530 N4=N1+N2+N3
540 V6=(400*N3+(330*N2)+(230*N1)+(420.6*N4))/2205+D[L]*0.02884
550 U6=V4*7.557
560 T6=V6*0.5422
570 H6=D[L]*63.02
580 M6=((D[L]*0.02838)^0.37)*230475.6
590 V7=D[L]*0.1763
600 U7=V7*0.7759
610 T7=V7*0.3716
620 H7=0
630 M7=22.53*D[L]
640 V=V1+V2+V3+V4+V5+V6+V7
650 U=U1+U2+U3+U4+U5+U6+U7
660 T=T1+T2+T3+T4+T5+T6+T7
670 H=H1+H2+H3+H4+H5+H6
680 M=M1+M2+M3+M4+M5+M6+M7
690 P1=D[L]-V
700 IF P1<0 THEN 840
710 P2=Y-U
720 IF P2<0 THEN 840
```

```
730 G=T/W
740 WRITE (0,750)W1,W2,W3,W4,W5,W6,W7,U1,U2,U3,U4,U5,U6,U7
750 FORMAT 2X,14F8.1
760 P1=P1/P[L]
770 P2=P2/Y
780 C=(((H*10.08+M*1.026)*1.242)+W2*42313)/1000
790 P3=C/P1
800 P4=(P1/P2)*1000
810 WRITE (0,820)P1,P2,R1,R2,P4,C,P3,G
820 FORMAT 2X,2F8.1,2F8.5,F8.2,2F16.6,F8.4
830 GOTO 910
840 N=N+1
850 WRITE (0,860)
860 FORMAT 5X,"PAYLOAD WEIGHT < 0"
870 GOTO 900
880 WRITE (0,890)
890 FORMAT 5X,"PAYLOAD VOL < 0"
900 IF N>4 THEN 940
910 NEXT L
920 NEXT K
930 DATA 5,10,20,30,40,50,60,80,100,120,160,200,240,300,400
940 STOP
```

APPENDIX IV - LISTING OF FUEL CELL SUBMARINE PROGRAM

```
10 N=1
20 INPUT N
30 DIM D[4],S[15],E[4]
40 FOR I=1 TO 15
50 READ S[I]
60 NEXT I
70 D[1]=1000
80 D[2]=2000
90 D[3]=5000
100 D[4]=10000
110 E[1]=500
120 E[2]=1000
130 E[3]=2000
140 E[4]=4000
150 K[1]=0.002825
160 K[2]=0.00279
170 K[3]=0.00272
180 K[4]=0.002665
190 L[1]=993
200 L[2]=1717
210 L[3]=3542
220 L[4]=6124
230 FOR K=1 TO 15
240 FOR L=N TO 4
250 S1=S[K]*1000
260 X=D[L]/1.025
270 V=(S1/(K[L]*((D[L]*0.9842)^(2/3))))^(1/3)
280 P9=1+0.2*LGT(25/V)
290 V=V/(P9^(1/3))
300 WRITE (0,310)S1,D[L],X,V
310 FORMAT /,/,10X,"SHP=",F7.0,6X,"DISPL=",F6.0,5X,"VOLUME=",F8.1,3X,"VEL=",F6.2
320 K1=S1*0.911+L[L]
330 W2=(K1*0.015873+S1*0.01796)
340 W3=(K1*0.02718+S1*0.003115)
350 W[1]=(S1*0.0001964)+9.43
```

```
360 V[2]=(S1*0.0002533)+15.15
370 V[3]=(S1*0.0002451)+44
380 V[4]=(S1*0.0005436)+82.3
390 V2=V2+V[L]
400 V1=V2*0.1451+D[L]*0.3628
410 V1=0
420 T1=V1*0.4953
430 H1=13800*((V1*0.0842)^0.57)
440 M1=220322.4*((V1*0.0842)^0.41)
450 V2=V2+V[L]*1.367
460 T2=V2*0.4505
470 H2=V2*679.1
480 M2=K1*500+S1*100+(V2*0.091+W[L])*4488.4
490 V3=S1/10000+(D[L]^0.5)/10
500 V3=V3*1.587
510 T3=V3*0.5371
520 H3=V3*679.1
530 M3=V3*4488.4
540 V4=D[L]*0.0066
550 V4=V4*1.5168
560 T4=V4*0.75
570 H4=((V4*0.0842)^0.76)*5980
580 M4=V4*10012.5
590 V5=D[L]*0.0665
600 V5=V5*1.238
610 T5=V5*0.5379
620 H5=((V5*0.0842)^0.59)*30130
630 M5=((V5*0.0842)^0.59)*161368
640 N1=INT(10+(S1/5000))
650 N2=INT(S1/20000)+2
660 N3=INT((S1/20000)^0.5)+2
670 N4=N1+N2+N3
680 V6=(400*N3+(230*N2)+(230*N1)+(420.6*N4))/2205+0.02884*D[L]
690 V6=N4*7.557
700 T6=V6*0.5422
710 H6=D[L]*62.02
720 M6=((D[L]*0.02828)^0.37)*220475.6
```

```
730 W7=D[L]*0.1760
740 W7=W7*0.7750
750 T7=W7*0.3716
760 H7=0
770 M7=0
780 WRITE (0,790)W1,W2,W3,W4,W5,W6,W7,U1,U2,U3,U4,U5,U6,U7
790 FORMAT 2X,14F8.1
800 IF X<10 THEN 820
810 X=10
820 W1=(X^2)*X[L]*(1+0.2*LOG(25/X))*0.011*((D[L]*0.0842)^(2/3))+W[L]/2
830 FOR J=1 TO 4
840 E=F[J]/X
850 W8=X1*E*0.0003628
860 W8=W8*0.25786
870 W9=W8*0.2
880 W9=W9/2.7122
890 T8=W8*0.5
900 H8=0
910 M8=0
920 M9=((W9*0.0842)^0.41)*2200200.4
930 T9=W9*0.5
940 H9=((W9*0.0842)^0.57)*12800
950 W=W1+W2+W3+W4+W5+W6+W7+W8+W9
960 U=U1+U2+U3+U4+U5+U6+U7+U8+U9
970 T=T1+T2+T3+T4+T5+T6+T7+T8+T9
980 H=H1+H2+H3+H4+H5+H6+H9
990 M=M1+M2+M3+M4+M5+M6+M7+M8+M9
1000 P1=D[L]-W
1010 IF P1<0 THEN 1170
1020 P2=X-W
1030 IF P2<0 THEN 1170
1040 P1=P1/D[L]
1050 P2=P2/X
1060 P4=(P1/P2)*1000
1070 C=T/W
1080 F1=F[J]
1090 WRITE (0,1100)F1,W8,W9,M9,H9,P1,P2,P1,P3,P4
```

```
1100 FORMAT 2X,F6.0,4F8.1,2F8.4,F8.2
1110 FORMAT 2X,2F16.6,F9.5
1120 C=((H*10.08+N*1.006)*1.242)/1000
1130 P3=C/P1
1140 WRITE (0,1110)C,P3,C
1150 NEXT J
1160 GOTO 1250
1170 IF J>1 THEN 1250
1180 N=N+1
1190 WRITE (0,1200)
1200 FORMAT 5X,"PAYLOAD WEIGHT LESS THAN ZERO"
1210 GOTO 1240
1220 WRITE (0,1230)
1230 FORMAT 5X,"PAYLOAD VOLUME LESS THAN ZERO"
1240 IF N>4 THEN 1280
1250 NEXT I
1260 NEXT K
1270 DATA 5,10,20,30,40,50,60,80,100,120,160,200,240,280,400
1280 STOP
```